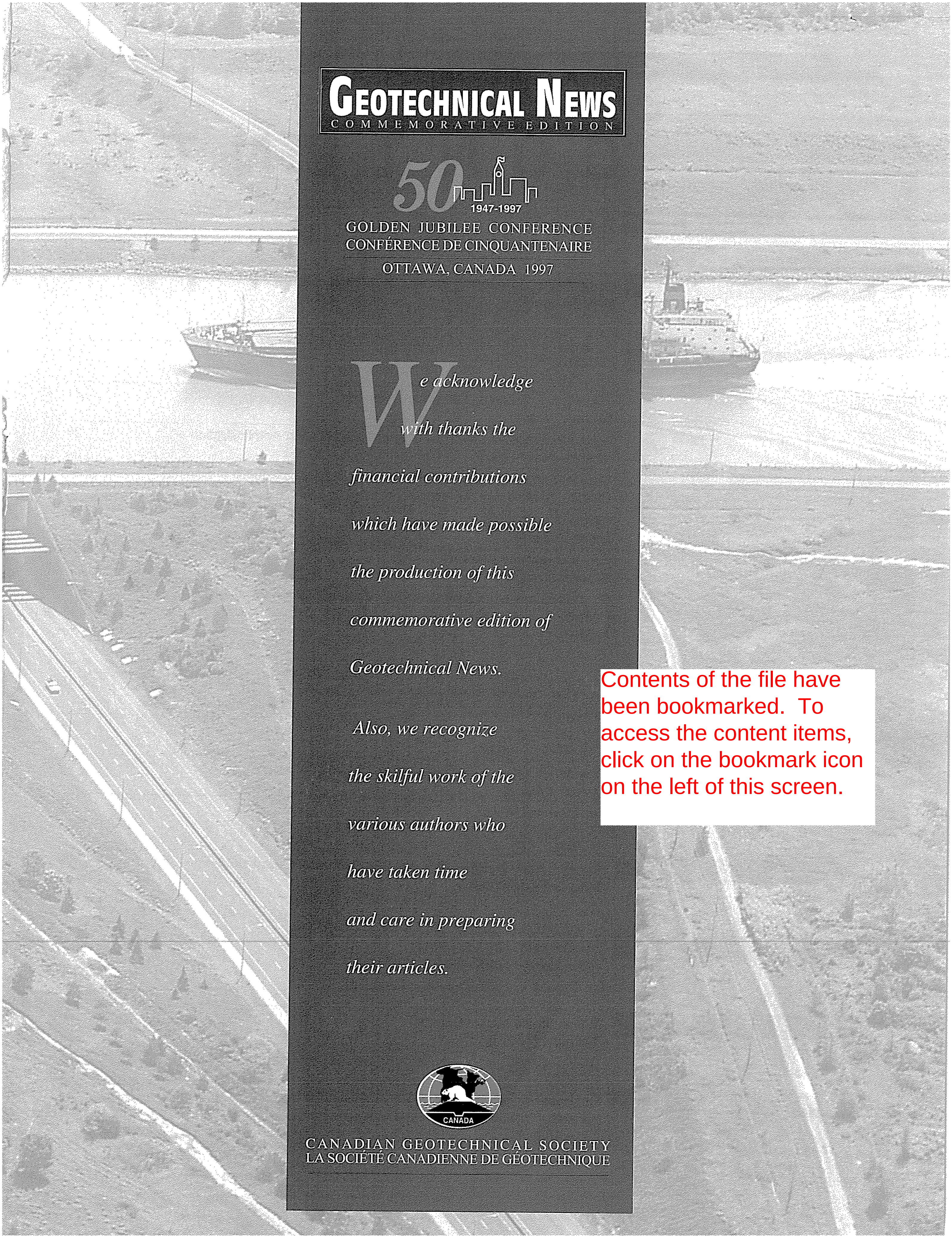

GEOTECHNICAL NEWS
COMMEMORATIVE EDITION

50 1947-1997

GOLDEN JUBILEE CONFERENCE
CONFÉRENCE DE CINQUANTENAIRE
OTTAWA, CANADA 1997

We acknowledge with thanks the financial contributions which have made possible the production of this commemorative edition of Geotechnical News.

Also, we recognize the skilful work of the various authors who have taken time and care in preparing their articles.

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CANADIAN GEOTECHNICAL SOCIETY
LA SOCIÉTÉ CANADIENNE DE GÉOTECHNIQUE

VOLUME 15
NUMBER 4
OCTOBER 1997

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ON THE COVER: *St. Lawrence Seaway. East Main Tunnel, Welland Canal*
Photo courtesy of the St. Lawrence Seaway Authority

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Publisher John W. Gadsby
Managing Editor Lynn Pugh
Graphics Pat Adams

COMMEMORATIVE EDITION

Guest Editor Cyril Leonoff
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Lynn Pugh
Victor Sowa
Bryan Watts

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In 1982 members of the Canadian Geotechnical Society conceived the idea of a book recording the development of geotechnical engineering in Canada. Since a number of the early practitioners were still living at the time, foremost among them Bob Hardy and Bob Legget, the approach was intended to create "a living history . . . through the eyes and recollections of living engineers, to show the humanity that underlies the development of major geotechnical projects in Canada." Approval in principle of the Heritage Book Project was given at the fall meeting of the CGS Board of Directors and a start-up grant allocated.

An Editorial Committee for the project was struck, chaired by David Townsend, while local correspondents were appointed across Canada, from Victoria to Halifax. A total of 88 taped interviews were recorded and transcribed. In early 1984 a name-the-book contest was announced and a detailed chapters outline prepared. Somehow the ambitious project died at this stage.

In 1992 an attempt was made to revive the Heritage Book Project, building on the original work. Because of my background, both in geotechnical practice and in historical writing, I was asked to submit a proposal to complete the book. The CGS Board supported the project "provided the necessary funding can be secured." But again the society seemed to lack the collective will to raise the necessary funding, and in the fall of 1983 the board decided "to abandon the project indefinitely."

At the 48th Canadian Geotechnical Conference, held in Vancouver in September 1995, appreciating that the Golden Jubilee Conference was fast approaching, the question of the history book was once more raised informally by a few interested members. This seemed to be the final opportunity to fulfill the project, inasmuch as the pioneer practitioners and projects were yet within the memories of senior society members.

Out of this conference, an ad-hoc volunteer committee arose composed of Jodi Everard, then president of the Vancouver Geotechnical Society, Bryan Watts, chair of the 48th Conference Organizing Committee, Lynn Pugh, managing editor of *Geotechnical News*, and the writer. Jodi and Bryan, assisted by Victor Sowa, took on the job of fundraising, Lynn took charge of the publishing, and I became editor. John Seychuk agreed to be the Eastern representative. The Vancouver Geotechnical SocietyBoard undertook to sponsor the project and to provide seed funding, by way of a Western contribution to the Jubilee Conference, to be organized and held in the East. The Canadian Geotechnical Society, under President Jim Laing and Director General Tony Stermac, gave their blessing to the project.

Since a small group of people could not hope to compile a valid history before the Jubilee deadline, the committee decided to invite over twenty senior geotechnical engineers across Canada to prepare articles on assigned topics, with the stipulation that the writing should be of a "narrative-historical nature rather than technical." The result has been gratifying, not only in the positive response of the engineers solicited, but in the calibre of their articles.

The result of the project is this special historical edition of *Geotechnical News*, which is being distributed to CGS members and attendees at the time of the Golden Jubilee Conference in Ottawa, October 20-22, 1997. We trust that this issue will be useful as a permanent record of geotechnical heritage in Canada.

Cyril E. Leonoff, Editor

Vancouver, British Columbia
October 1997

Geotechnical Engineering in Canada An Historical Overview

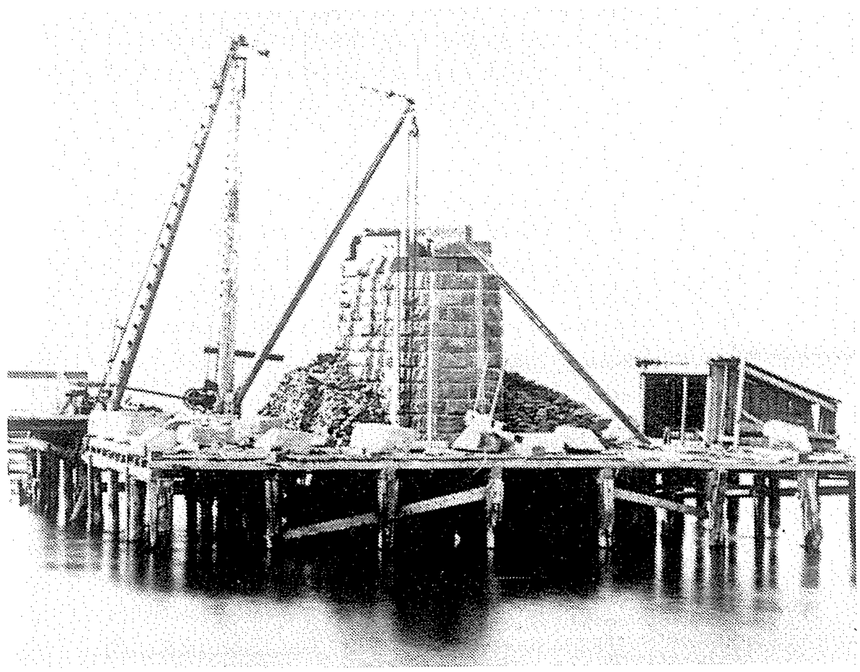
Cyril E. Leonoff

Terrain of Canada

The diverse, unconsolidated sediments comprising the earth's crust, broadly described as soil, constitute so large a portion of the earth's surface that few civil engineering projects can be carried out without dealing with some type of soil. As well, some of the largest man-made structures ever built — earth dams, dykes, canals, tunnels, railroads, and highways are composed largely of earthwork.

The civil engineers charged with the physical building of Canada have faced an awesome challenge. Geographically it is the third-largest country in the world, comprising the northern 40 percent of North America, bounded by three oceans and covering a land area of 3,851,809 square miles. Spanning the continent a distance of 3,842 road miles, between the Pacific at Vancouver, British Columbia and the Atlantic at Halifax, Nova Scotia, Canada has a scant population of some 30 million — barely eight persons per square mile — with 90 percent of these people strung along the southern border. Yet much of the mineral, oil, and water resource base to be exploited lies in the remote north and offshore.

The Pleistocene geology of Canada is prevalent. Canada has the largest glacial soil mantle of any country (indeed an almost complete absence of unglaciated areas and their residual soils) and correspondingly the largest area of enclosed fresh water. The geomorphology ranges from the lowlands of Hudson Bay, the Eastern Arctic, and the St. Lawrence Valley, through the Precambrian Shield where the soil mantle is thin and bedrock exposed, across the interior plain of the Prairie Provinces, to the Cordilleran mountain ranges of the far West.



Preloading of the NW Miramichi Bridge of the Intercolonial Railway, New Brunswick in 1874. (PA 22044)

The problems to be solved in Canada by the geotechnical engineer are seemingly endless. About half of the land is underlain by permanently frozen ground, or permafrost. Some 500,000 square miles are covered by sphagnum moss and decayed and fossilized vegetation, popularly called muskeg. Sensitive marine clay of the Champlain Sea — Leda Clay — lies in the St. Lawrence and Ottawa valleys; the lacustrine clay of infilled glacial lakes fills areas such as that around Lake Agassiz in Manitoba. Treacherous clay-shale — Bearpaw Shale — underlies much of the Prairies. Massive rock slides, such as the Frank and Hope slides, occur in the Cordillera, while great landslides also happen in the dry silt benches of the Thompson River railway belt, and "drowned valley clay" covers the floor of the Pacific Coast tidal estuaries and fjords. Moreover more than half of the Canadian population is subject to potential seismic hazard.

Early Civil Engineering Works

The challenges faced by the early 19th century Canadian civil and military engineers involved the construction of canals and locks, used to connect water transportation routes and to provide military defence — Welland Canal (1824-1829) and Rideau Canal (1826-1832). The construction of railways and their appurtenant works, such as bridges and tunnels, began in the 1830s-40s, serving to connect the scattered segments of the fledging nation — the

Grand Trunk between Sarnia and Montreal (1845-1862), the Intercolonial to the Maritime Provinces (1858-1876), and the Canadian Pacific (1881-1886) to the West.

By mid-century, engineered roads were being constructed for communication and transportation between settlements and for resource exploitation — the Cariboo Wagon Road (1862-1866) from Yale, B.C. through the Fraser Canyon to the gold-rush town of Barkerville, and the Dawson Road (1868-1870) to connect the missing links of the water route from Fort William to Red River. The former, built by the Royal Engineers, ranks with the greatest engineering achievements of the 19th century.

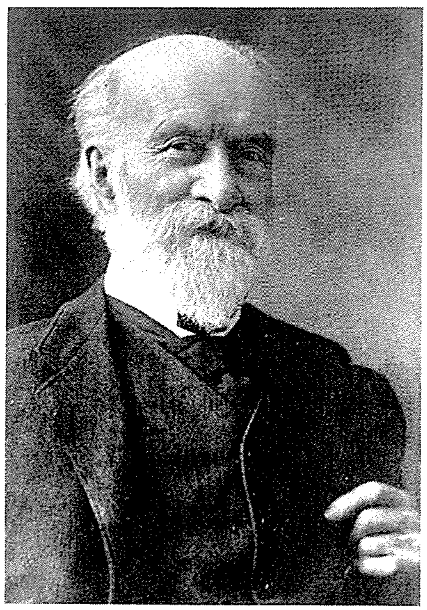
As the villages and towns grew into cities, dams and water supply reservoirs were required for domestic consumption, water power, and industry. Commensurate with the status of the new Canadian Confederation of 1867, at the end of the 19th— early 20th centuries, monumental public buildings made their appearance, sometimes with attendant settlement problems — the Empress Hotel, Victoria, and the Victoria Memorial Museum, Ottawa being prime examples.

The science of soil mechanics and the formal practice of geotechnique were to be events of the 20th century. Nevertheless, before the analytical tools invented by Karl Terzaghi were available, good civil engineers, by empirical methods, were able to devise solutions that were precursors of modern geotechnical engineering practice.

Sir Sandford Fleming (1827-1915) was Canada's preeminent railway engineer of the 19th century. Born in Scotland, where he studied surveying and engineering, Fleming came to Canada in 1845 at the age of eighteen and entered the service of the Northern (Ontario, Simcoe and Huron) Railway. His first great "empire-building" achievement came as chief engineer (1868-1875) of the Intercolonial Railway, which came about as a condition of bringing the Maritime Provinces into the Canadian Confederation.

The most noteworthy engineering work on the line was the construction of two 1,200-foot-long truss-span bridges over branches of the Miramichi River near Newcastle, New Brunswick. Initial test borings arranged by Fleming at the two river crossings, and surface outcropping inferred a sandstone bedrock. However during construction, when settlement of the northwest bridge piers was observed, Fleming stopped construction and ordered a second set of borings. At the southwest bridge, a dense gravel and sand stratum, underlain by a sandy-silty glacial till, allowed safe construction of the bridge piers to the original design.

However, at the northwest bridge, the bearing stratum was underlain by a thick deposit of clay-silt — the cause of the settlement. Fleming devised the first recorded static penetration tests, using cased iron rods within the bore holes to eliminate friction, in order to determine the loads which the different strata in the riverbed would support.



Sandford Fleming.

As a result of the tests, Fleming proceeded to enlarge the pier bases in order to spread the load, and he preloaded each pier until the settlement stopped.

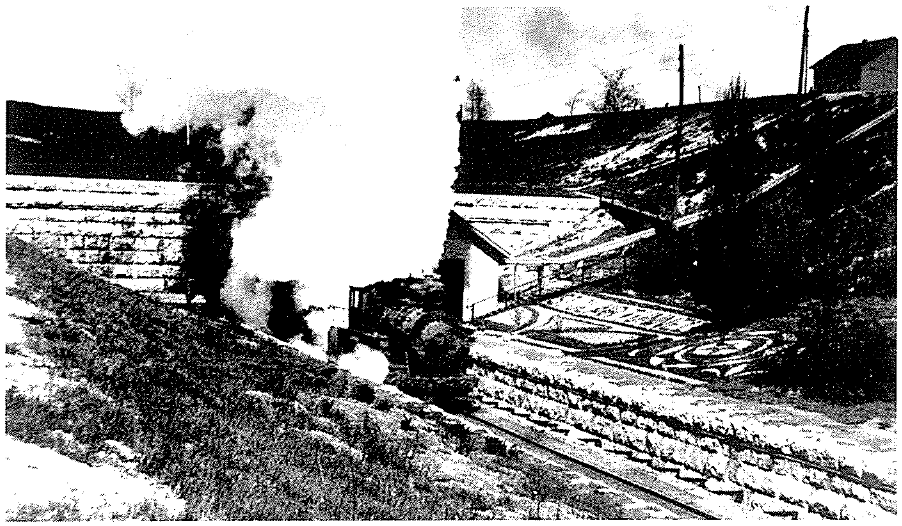
In 1871 Sandford Fleming was appointed engineer-in-chief to superintend the surveys for the Canadian Pacific Railway through the Rocky and Selkirk Mountains. He surveyed the route through the Yellowhead Pass, which is now followed by the Canadian National Railways, and he was the first to demonstrate the practicability of the CPR route through the Kicking Horse, Rogers, and Eagle passes.

After 1880 Sandford Fleming devoted himself to scientific and literary work. Among his many other achievements, he was the pioneer of the 24-hour system of time reckoning and of standard time, necessary for the scheduling of transcontinental train service. Fleming also designed the first Canadian postage stamp, the three-penny issue of 1851. It depicts the beaver, that ubiquitous resourceful civil engineer of the Canadian wilderness, building his dam.

Now operated by CN Rail, the Grand Trunk Railway initiated the St. Clair Tunnel, built between Sarnia, Ontario and Port Huron, Michigan from 1889-1891. The tunnel replaced a slow ferry service in providing a primary Canadian link to Chicago, centre of the North American railway universe. After two previous attempts had failed, the Grand Trunk chose the experienced civil engineer Joseph Hobson, born in 1834 at Guelph, Ontario, as chief engineer of the tunnel company. Hobson's "combination of daring, tenacity, and engineering knowledge" proved to be just the right combination to ensure success of the venture. In investigating the site, Hobson made detailed borings in line

Canada Three-Penny Beaver Stamp, 1851.

with the proposed route, taking 110 soil samples. These revealed that the riverbed consisted of a thin layer of "treacherous blue clay" above a shale bedrock. To execute the large bore tunnel, two huge cylindrical shields with knifelike leading edges were driven from each end by hydraulic rams through the "slippery" clay "like a giant cookie cutter." The clay layer above the crown was so thin — only 10 to 12 feet — that the workers claimed that they could hear the bands playing aboard steamers passing overhead. This first international tunnel in North America, driven subaqueously through such perilous clay, was widely reported in trade journals throughout the world and considered an engineering marvel of the day. Many of the precedent-setting techniques employed in the project have been adopted in modern tunnel engineering practice. Hobson's tunnel survived a century of active service but has recently been replaced, not because of any failure in its engineering, but because its dimensions were made obsolete by inter-modal rail systems such as double-stack container cars and tri-level auto cars.



St. Clair Tunnel Co. 0-10-0 engine emerges from the Sarnia portal, "amid a cloud of steam and smoke," ca. 1900 Lambton County Library.

Joseph Hobson (CN81071)

Samuel Fortier

Born in Leeds, Quebec, Samuel Fortier (1855-1933) graduated in civil engineering from McGill University in 1885 and later received a master's degree from this university. In October 1896 Fortier read a paper, "The Storage of Water in Earthen Reservoirs," before the Canadian Society of Civil Engineers, which earned for its author the Gzowski Medal, the senior technical award of the society. In it he anticipated the factors that would be considered by a modern soil mechanics engineer: "An intimate knowledge gained from a close study and carefully made tests of the physical.... and mechanical ... properties of the materials.... the size and weight of the grains, the amount of air-space they enclose, the percentages of air and water contained in these open spaces, and the effects produced by moisture, heat and frost, as well as the action of such forces as gravity, capillarity and evaporation [and] the mode of compacting reservoir embankments." Fortier further recognized that "the proper widths and slopes to adopt in the building of earthen dams cannot as yet be determined by mathematical calculations [but] the dimensions in each particular case must be left to the good judgment, practical skill and the knowledge gained from experimental tests, of the designing engineer."

Fortier is less well known in Canada than in the Western United States, to which he emigrated and gained repute as a water works and agricultural irrigation engineer in Colorado, Montana, and California.

In 1897 civil engineer Robert Brewster Stanton, who had thirty years' experience in the Rocky Mountain region from Canada to Mexico, read a paper before the British Institution of Civil Engineers on the great landslides that had occurred on the Thompson River near present-day Ashcroft, British Columbia, at the time of construction of the Canadian Pacific Railway in the 1880s. Within a distance of some five miles there were several large landslides, six crossing the railway line, as well as a number of smaller slips. Twenty miles farther down the river, at a point opposite Spences Bridge, there was a similar large slide. Three of the slides were of giant proportions. The largest, the 100-million-ton Great North Slide of October 1881, actually blocked the river for 44 hours, causing a huge flood. Stanton, after careful observations, attributed the slides to irrigation of the silt terraces above the river, which when saturated lost strength and collapsed into the river. More recent soil mechanics examination has indicated that the silt is finely layered with clay and that the seat of shearing may have been in the clay. As both transcontinental rail lines CP and CN still traverse these slides, there is yet some local manifestation of slide action on a smaller scale.

The failure of the Transcona Grain Elevator, built in the glacial Lake Agassiz basin near Winnipeg, Manitoba is a classic case of shear failure of a heavy structure on a raft foundation, built on a thick layer of soft saturated clay. Filling of the bins of the million-bushel elevator began in September 1913. When 875,000 bushels of wheat were stored, a vertical one-foot settlement was noted within an hour, then the structure began to tilt to the west, and within 24 hours came to rest at an angle of 26° 53′ from the vertical. The west side was 29 feet below and the east side 5 feet above original grade. The rigid monolithic structure, built on a two-foot-thick reinforced-concrete raft, showed little damage other than a few surficial cracks. The elevator was righted and underpinned by the Foundation Company of Canada on piers sunk 54 feet to the limestone bedrock.

A later study in 1952, carried out jointly by the Division of Building Research, National Research Council of Canada and the University of Manitoba, confirmed an ultimate bearing capacity of 6,200 pounds per square foot, which correlated very closely with the theoretical value based on a soil mechanics analysis.

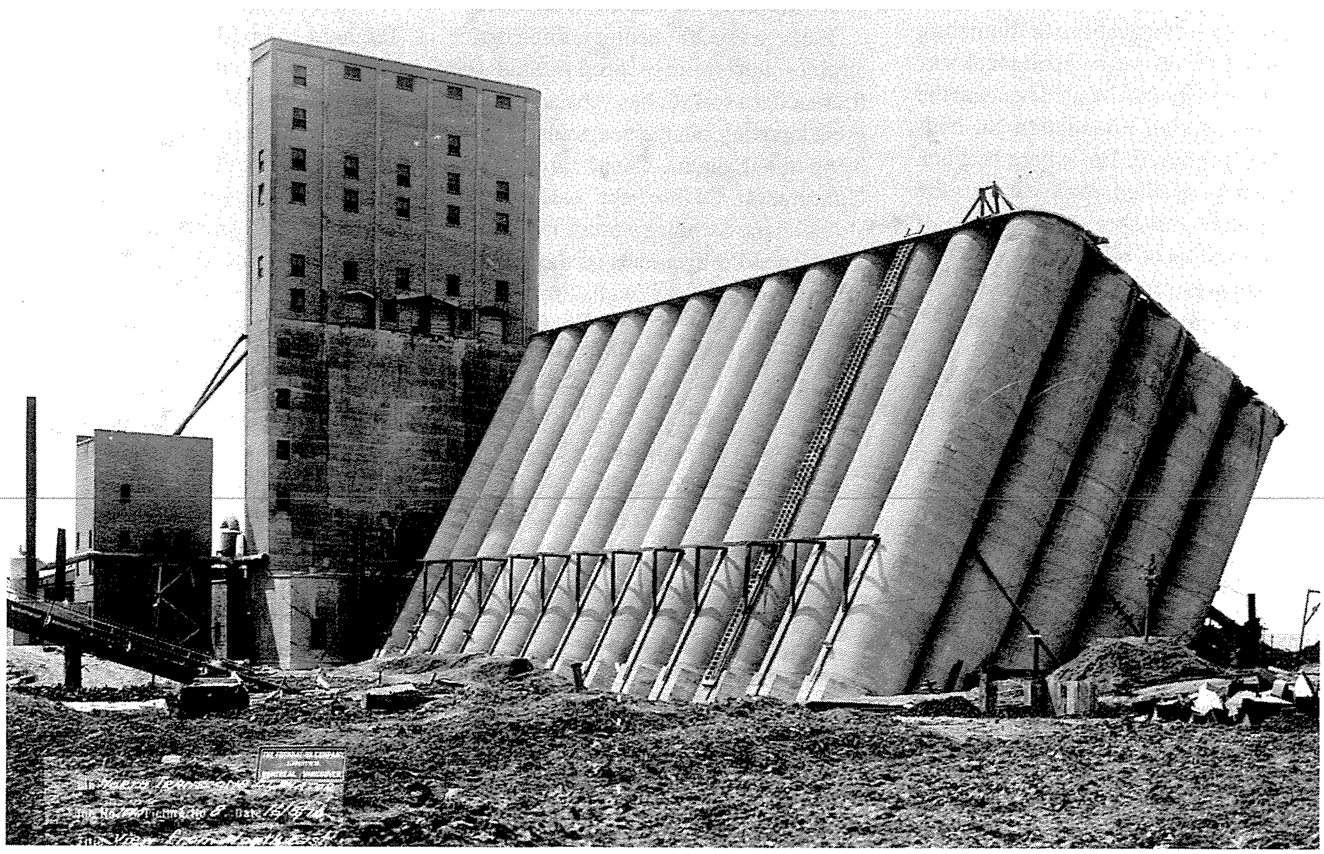
Two Canadian cases of recorded long-term building settlements, erected before the science of soil mechanics was applied to building foundations, are also noteworthy.

Construction of the CPR Empress Hotel at James Bay, Victoria began in 1904 on a site reclaimed from the sea. Marine clay underlies the building to a thickness ranging from a few feet to more than 100 feet. The building was constructed on a foundation of 1,853 timber piles, each about 50 feet long. Observations began in 1912, after settlements were first noticed, and have continued ever since.By 1971 the differential settlement across the building from north to south amounted to some 30 inches, although this was not noticed by the casual visitor.

After 50 years of service, the owners were faced with the decision whether to extend the life of the elegant structure or to replace it with a modern building. On the basis of a comprehensive study, R.M. Hardy concluded that the rate of settlement was decreasing and would be within acceptable limits. As a result, in a multi-million dollar program, the building was rehabilitated under the appropriate name Operation Teacup.

The Victoria Memorial Museum (National Museum of Canada) building in Ottawa, a massive four-storey structure, 400 feet long and 150 feet wide, with heavy sandstone bearing walls, rested on spread footings. Since completion of the building in 1910, footing loads, which varied from 12 to 4 tons per square foot, caused a differential settlement in 40 years of more than 1 1/2 feet.

Unlike the Empress Hotel, the building showed distress from the start and was completed with much difficulty. Basement and ground floors and the exterior walls, supported on both exterior and interior footings, showed severe distortion and cracking. The upper storeys, carried on plate girders spanning the exterior walls, suffered less differen-



Transcona Grain Elevator failure, October 1913
The Foundation Company

tial settlement. By 1916 a tower at the front of the building was out of plumb by more than a foot and the upper portion had to be removed to prevent complete failure.

In the early 1950s, borings and studies of the museum by DBR/NRC revealed that the building was underlain by 50 feet of sensitive, compressible marine (Leda) clay, which graded into clayey silt, sand, and glacial till at increasing depth, with bedrock at 132 feet.

Birth of Soil Mechanics

Prior to the 20th century, any textbook on foundation and earthwork engineering divided soil into several categories — gravel, coarse and fine sand, silt, and soft or stiff clay. Various allowable bearing values, based on empirical equations or rules, were assigned to these different materials. But only one variable, the type of soil, was considered. Equally important mechanical properties of the soil, such as density, water content, and compressibility were ignored.

In those early years, the foundation design of buildings or of structures involving deep excavation or tunneling was based on primitive geological surveys of the materials located beneath the construction site. Foundation on bedrock was preferred. But where bedrock could not be reached, over soft soils the bearing load was spread out by use of spread footings or rafts, often with disappointing results, as we have seen with the Victoria Memorial Museum and the Transcona Grain Elevator.

When in doubt, pile foundations were the rule. At the beginning of the 19th century, empirical pile formulas were developed, with the bearing capacity of each pile computed on the basis of the work performed by the hammer in driving the pile into the ground, the depth of the pile's penetration, and the resistance of the soil. While helpful, these formulas did not preclude the possibility of an entire group of piles settling. If the pile tips were located above clay soil, excessive settlement often took place as a result of the gradual consolidation of the clay soil beneath the piles, as we have noted with the Empress Hotel.

The mechanics of landslides were not understood, and rational methods for evaluating the safety of slopes with respect to sliding were unknown. The only analytical tools at the disposal of civil engineers were the theories of earth pressure on retaining walls, and the natural angle of response at which a soil mass would remain stable, as enunciated by C.A. Couloumb in 1776 and W.J.M. Rankine in 1856. However, because of their simplified assumptions on the behaviour of soil, these theories had little practical usefulness outside of the classroom.

Humankind had been constructing earth dams for at least 2,000 years, usually for the purpose of creating water storage reservoirs. Yet the height of such construction was limited to about 100 feet before collapse. Dam failures were widely reported in the engineering literature, when the mechanics of seepage, pore-water pressure, and piping in cohesive soils were still undiscovered. Few engineers had the perspicacity of Samuel Fortier, and systematic methods for compacting the soils used to construct the dam remained undeveloped.

Early in the 20th century, three major engineering failures precipitated the first modern soil studies. These were the great landslides in the deep cuts made to bring the Panama Canal through the Continental Divide, the catastrophic slides on the Swedish state railways, and the outward movements of the massive pile-supported quay walls in the construction of the Kiel Canal between the North and Baltic seas. In 1913, the situation in Panama, as well as continuing dam failures and building settlements, led the American Society of Civil Engineers to appoint a committee to look into these matters. The committee stressed "the importance of expressing the properties of soils by numerical values." Similar realizations came in Europe.

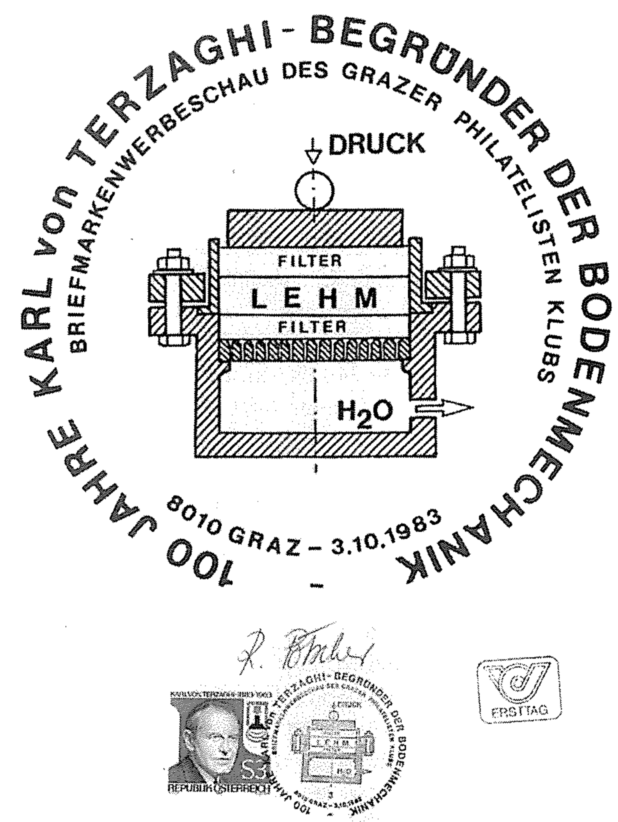
Seldom has one man dominated a discipline as did Karl (Charles) Terzaghi (1883-1963) in the field of soil mechanics. An Austrian, he studied mechanical engineering and geology, receiving a mechanical engineering degree in 1904, and later a doctor of technical sciences, from the Technical University of Graz. For six years preceding World War I, he worked on a variety of engineering and construction projects in the Alps, in Croatia, and in northern Russia, where he was able to absorb the practical side of civil engineering. In particular, problems which arose in constructing the foundations of a large building in St. Petersburg, where he had opportunity to observe "the incompetence of the engineering profession in the field of earthwork engineering," piqued his interest and set Terzaghi on his life mission to find a rational basis for predicting the performance of soils in earthwork and foundation engineering.

At this time, the United States Reclamation Service was doing pioneering work on a large number of dams and irrigation works in the Western States under a wide range of geologic conditions. With the agreement of the director, Terzaghi spent two years in America studying case histories of these projects. But he returned home at the end of 1913 disillusioned, because he had failed to find the "missing link," the correlation between the performance of a foundation and the geologic characteristics of its site.

At the beginning of World War I, Terzaghi enlisted in the air force of the Austrian army. However, in 1916 he was posted by the Ministry of Foreign Affairs to Constantinople, Turkey, to lecture on foundations at the Imperial School of Engineers — the present Technical University of Istanbul (The Ottoman Empire sided with the Central Powers and the institution was under German influence.). There Terzaghi began a study of all German, French, and English literature on the subject. At the end of the war, the victorious Allied Powers occupied Constantinople and the teaching staff, including Terzaghi, were summarily dismissed.

At this nethermost point in his career, Terzaghi felt humiliated, depressed, and without any means of support. He had "no urge whatsoever to teach" inasmuch as he was "too deeply preoccupied with [his] own ignorance." Soon enough though, he was offered an appointment at Robert College —now Bogaziçi University — in Istanbul, an English-speaking school founded by American missionaries. In a flash of inspiration, Terzaghi visualized what was needed to obtain a rational approach to the problems involved in earthwork and foundation engineering. Progress depended on the development of testing equipment which could provide a quantitative measure of the properties of the soils involved. On two sheets of paper, he listed a number of possible ways to test soils, made sketches of the equipment needed, and suggested how the results could be interpreted. Terzaghi had finally made his fundamental discovery: "Engineering geology cannot become a reliable tool in the hands of earthwork engineers unless and until we acquire the capacity to assign to each material of the earth numerical values."

Within a few weeks of beginning work at Robert College, Terzaghi had set up a small laboratory in the engineering building. During the week the lab's lights were to be seen burning well into the night. Weekends were spent on expeditionary field trips along the Bosporus and the Marmara Sea. Having scant funds, Terzaghi had begun seven years of "strenuous experimentation" with soils, using borrowed measuring devices and apparatus built with odds and ends scrounged from the college dump. His first earth-pressure apparatus was made from empty cigar boxes, and his loading devices consisted of empty oil cans filled with sand. In Terzaghi's first American article, "Old Earth-Pressure Theories and New Test Results," published in 1920 in *Engineering News-Record*, in which he discarded the theories of Coulumb and Rankine,he described the small-scale experiments that established the relationships between earth pressure and the lateral deformation or yielding of a mass of soil. Earth pressure against retaining walls, braced cuts, and anchored bulkheads, as well as arching over tunnels and around shafts, are dependent on this relationship. In 1925, with the publication of Terzaghi's first book, *Erdbaumechanik*, the science of soil mechanics emerged from its academic womb.



Republic of Austria Post, first day cover, centenary of birth of Karl Terzaghi, 1883-1983, September 23, 1983.

From the fall of 1925 until October of 1929, Karl Terzaghi spent his second period in the United States, this time at the Massachusetts Institute of Technology, where numerous new buildings were undergoing large and continuous settlements. While at MIT he codified the equipment needed for soil testing. There he made the acquaintance of Dr. Arthur Casagrande (1902-1981), who was to become his principal associate throughout the second half of Terzaghi's career. Like Terzaghi, Casagrande was a native Austrian. He had graduated from the Technical University in Vienna before coming to the United States in 1926 with no real prospect of work. He gained an interview at MIT, met Terzaghi and immediately began to work for him. In 1934 Casagrande moved on to Harvard University becoming Professor of Soil Mechanics and Foundation Engineering. Terzaghi trained several other men who would go on to eminence in soil mechanics, and his tenure at MIT can logically be considered the birth of soil mechanics in America.

Terzaghi returned to Vienna in 1930 as a professor at the Technical University, where his department soon became a renowned centre of soil mechanics, attracting students from many countries. And he continued to consult on important projects throughout Europe, North Africa, and the Soviet Union.

In 1936, as part of the Harvard Tercentenary celebrations, Arthur Casagrande, as Conference Secretary, convened the First International Conference on Soil Mechanics and Foundation Engineering, with Karl Terzaghi as Conference President. Despite Terzaghi's initial misgivings that it was premature, the conference was a great success, attracting 206 delegates from 20 countries. At this meeting, Terzaghi and Casagrande were commissioned to set up an executive committee to continue the work of the conference, an action which became the catalyst for establishment of the International Society for Soil Mechanics and Foundation Engineering (ISSMFE).

In 1936 Terzaghi became a visiting lecturer at the Harvard Graduate School of Engineering. After Hitler occupied Austria in 1938, Terzaghi moved permanently to Harvard, becoming Professor of the Practice of Civil Engineering, where he taught courses on engineering geology and applied soil mechanics. He also lectured at the Imperial College of Science and Technology in London, England, at MIT, and at the University of Illinois. His 1948 book, *Soil Mechanics in Engineering Practice*, coauthored with Professor Ralph B. Peck of Illinois, became the seminal text for all engineers practicing in the field of soil mechanics. Terzaghi also produced more than 100 scientific papers during his career.

Terzaghi was never content to restrict his work to experimenting in the laboratory or theorizing at his desk. Early in his career he realized that soil mechanics could only be successfully applied as a tool in engineering practice through a capacity for judgment based on years of contact with actual field conditions. Whereas the designer of structures deals with steel and concrete, whose properties are constant when manufactured in accordance with standard specifications, the designer of earthwork engineering has to apply the laws of mechanics and hydraulics to an infinite variety of heterogeneous materials formed as a result of natural processes. Design assumptions have always to be verified or modified by observing, first hand, soil conditions as they are exposed and measured during construction. In his paper, "Soil Mechanics in Action," Terzaghi succinctly outlined his approach: "Soil mechanics will not consistently serve its purpose until practicing engineers come to realize that it is a supplement to, and not a substitute for, common sense combined with knowledge acquired by experience."

When Terzaghi's controversial theories began to circulate outside of university walls, they were first met with skepticism among American civil engineers. But, as their validity was consistently demonstrated in practice, Terzaghi's stature in the engineering profession became universally acclaimed, and his expertise as a consultant was avidly sought in many parts of the globe. But he carefully husbanded his time, accepting only those assignments that advanced the science and demanded artful, novel solutions.

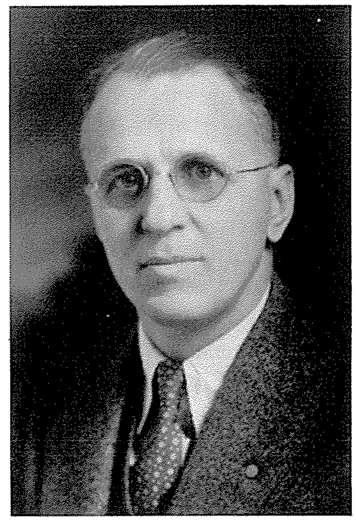
Terzaghi's first exposure to the soils of the Pacific Northwest came during his visit to the United States in 1912-1913, when he had an opportunity to observe the instability of clay slopes in Washington and Oregon. In 1929, as Professor of Foundation Engineering at MIT, Terzaghi was engaged by the industrial engineers V.D. Simons Inc. of Chicago, designer of the Grays Harbor Pulp and Paper Mill in Hoquiam, Washington. Terzaghi was asked by this firm to analyze the cause of settlement which was occurring beneath the mill's foundation piles at tidewater. In a landmark report containing detailed computations, Terzaghi determined that the settling was not, as previously believed, the result of "the weight of fill forcing the piles into the ground." In fact settlement occurred "as if the piles were non-existent." The settlement was due to the gradual consolidation of a soft clay layer, 30 to 50 feet thick, located at a depth of 120 feet below the surface of the tidal flat, later described by Terzaghi as "drowned valley clay."

The field engineer on the Grays Harbor job was the boss's son, Howard A. Simons. H.A. Simons later moved to Vancouver, British Columbia, where he established the international engineering company that bears his name. Faced with the design of a number of pulp mills on Vancouver Island, having similar tidewater conditions, in 1945 Simons brought Terzaghi to B.C. as a consultant. Terzaghi found British Columbia much to his liking, enjoyed its beautiful scenic landscape, and was attracted to the experience of participating in the development of a new country with many technical challenges. Here, during the last decade-and-a-half of his consulting practice, Terzaghi found many of his most challenging projects, on the foundations of pulp mills, and on hydroelectric and water supply dams.

Canadian Soil Mechanics Pioneers

Ibrahim Folinsbee (Ibe) Morrison (1889-1958) is regarded as the father of soil mechanics in Canada. Born near Boston, Massachusetts, he received his civil engineering degree from MIT in 1911. Morrison joined the University of Alberta as a lecturer in civil engineering in 1912, and was appointed Professor of Applied Mechanics in the civil engineering department in 1922. Commencing with the first graduation class, Professor Morrison, having a keen mind and a gift for sharp dialogue, taught and inspired virtually every engineering student at the university for over four decades.

I.F. Morrison was a perpetual student. Self-taught in German, he read Terzaghi's and other works, and began to introduce soil mechanics into his courses. By 1925 "Foundations" was recognized as a subject in the fourth-year civil engineering curriculum. In 1930 an elementary soils laboratory was set up for classification tests, and by 1931 soil mechanics was recognized as a separate segment of the foundation course. In 1936 Morrison was one of eight Canadians to attend the First International Conference on Soil Mechanics and Foundation Engineering at Harvard. In 1937 his course was officially



I.F.Morrison
Harold Morrison

designated Soil Mechanics and Foundations. Active in professional practice and research, Morrison contributed extensively to technical discussions in Canada and the United States, and authored textbooks and papers. "The Fundamentals of Pile Foundations," published in 1939 in *The Engineering Journal*, was an early paper on the subject of foundations.

Robert M. (Bob) Hardy (1903-1985) graduated as a gold medallist in civil engineering from the University of Manitoba in 1929 and received his master's degree in 1930 from McGill University, specializing in structural engineering. In September 1930 he joined the Faculty of Engineering at the University of Alberta as a sessional lecturer. Professor I.F. Morrison encouraged his bright, younger colleague to take the soil mechanics courses at the Harvard Graduate School of Engineering taught by Casagrande and Terzaghi, which Bob Hardy did in 1939-1940.

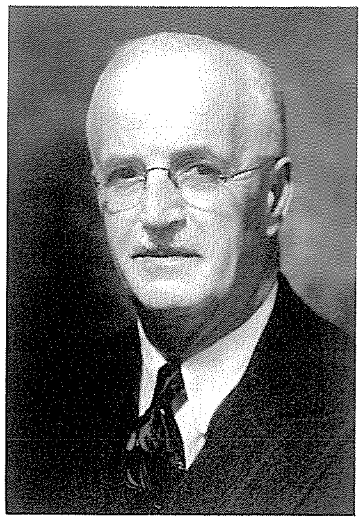
When he returned to Alberta, Hardy established a state-of-the-art soil mechanics laboratory, and by September 1945, a graduate program. In 1946 he was appointed Professor, Head of the Department of Civil Engineering and Dean of Engineering. Thus, under the impetus of Morrison and Hardy, the University of Alberta became the first soil mechanics school in Canada, attracting large numbers of students from every province and from many countries abroad.

Robert M. Hardy
Charles Ripley

The beginning of applied soil mechanics in Canada dates as early as 1928, when Morrison and later Hardy commenced a long-lasting consulting association with Montreal Engineering Company and Calgary Power in the design and construction of several early power projects in Alberta. In 1942-43 Hardy carried out research studies on muskeg and permafrost for the US Army Corps. of Engineers, who were then hastily constructing the Alcan Military Highway—the first such studies conducted in North America. During the war Hardy also consulted on Canadian airports, then being built from Vancouver Island to Newfoundland.

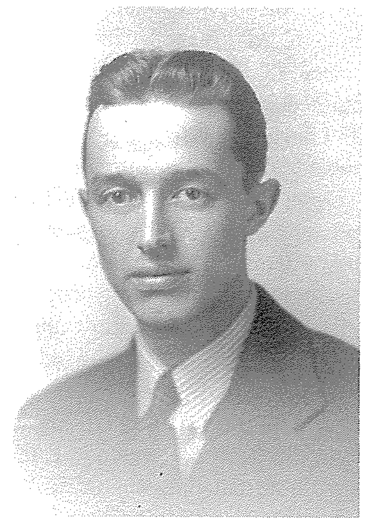
In April 1951, Hardy, along with L.A. (Chick) Thorssen, a concrete specialist, established Engineering and Construction Services, a commercial soil and concrete testing laboratory in Edmonton — one of the first in Canada. After Thorssen left, in 1954 the company was renamed R.M. Hardy and Associates. During the remainder of his long career, Hardy carried on an extensive consulting practice and was widely regarded as the eminent soil mechanics consultant in Canada.

Concurrent with Morrison's and Hardy's work, the other significant application of soil mechanics in Canada was initiated by the Prairie Farm Rehabilitation Administration, a federal government agency that was building water conservation projects in Alberta, Saskatchewan, and Manitoba. Since its inception in 1935, the PFRA had been helping drought-stricken farmers to build small earth dams and reservoirs on their properties. By 1939 the agency was becoming involved in a few larger dams intended to provide reservoirs for entire communities, and the soil problems inherent in these structures were being encountered.



C.J.Mackenzie
University of Saskatchewan Archives

The catalyst in introducing soil mechanics to the PFRA was Dean C.J. (Chalmers Jack) Mackenzie (1888-1984) of the University of Saskatchewan. Born in St. Stephen, New Brunswick, in 1909 Dr. Mackenzie had earned his engineering degree from Dalhousie University and in 1915 his master of civil engineering from Harvard University. In 1912 he joined the University of Saskatchewan as a sessional lecturer. After serving in the Canadian Expeditionary Force, 1916-1918, in World War I, and being awarded the Military Cross, he returned to the university, becoming first Dean of the College of Engineering in 1921. Mackenzie, a structural engineer, was a consultant on civil engineering projects across Western Canada — among them in 1932 the design of the Broadway Bridge, a reinforced concrete arch structure in Saskatoon, and in 1935-1937 a reinforced concrete bridge across the North Saskatchewan River at Borden. On these major projects, Dr. Mackenzie realized the need for the application of soil mechanics technology to the design of bridge foundations. One of Mackenzie's brightest graduate students was David Kirkbride, who worked on construction supervision of the Borden Bridge.



David Kirkbride
Michael Kirkbride

David Spencer Kirkbride (1913-1995) was born in Calgary. But at the age of four, when his lawyer father died, he came to Regina with his mother (Isabelle Spencer) to live with her parents. David graduated from Central Collegiate, winning the Governor General's Bronze Medal, then attended the University of Saskatchewan, 1930-1937, where he earned a bachelor's degree in civil engineering and a master's degree majoring in structural.

Upon graduation, finding no employment in Saskatchewan, Kirkbride obtained work with Monsarret and Pratley, bridge engineers in Montreal, but when that job petered out, he moved on to Canadian Industries Limited in that city to work as a draftsman.

Through his contacts with Mackenzie and the bridge firm, Kirkbride became aware of the developments taking place in soil mechanics and foundation engineering. He approached the leading foundation firm in Canada, the Foundation Company in Montreal, proposing that they should employ him, sponsor his graduate training at Harvard, and thereby gain the benefit of soil mechanics knowledge on his return. But they were skeptical of the practical application of the new science, and nothing came of this. Nevertheless, Kirkbride applied to Harvard Graduate School, obtained a scholarship, and in 1938-1939 became the first Canadian to earn a master's degree in soil mechanics.

Upon graduation, Kirkbride tried to persuade the Dean of Engineering at McGill University to introduce soil mechanics into their teaching program, but at the time the Dean didn't appreciate that the subject was worthwhile. However the PFRA was planning some larger dam projects and Dr. Mackenzie was influential in persuading this organization that they should utilize the soil mechanics training that Kirkbride had acquired at Harvard. He was hired on staff as a junior engineer. Kirkbride worked for the PFRA only from his graduation in June through October 1939. During this short period, he set up the first elementary wash-bore drilling equipment, used to augment the digging of test pits and the boring of auger holes, the methods heretofore used which were limited in depth. Kirkbride also recommended to management the need for laboratory facilities, and gave some preliminary soil mechanics advice on a few dam sites. War came in September 1939, and knowing that the PFRA activities would be curtailed during the war, Kirkbride returned to CIL to work in the war effort with its wartime counterpart Defence Industries Limited.

Kirkbride spent the remainder of his substantial career with DIL and CIL, first in the engineering department, which greatly expanded in the war, then as resident engineer on the Atomic Energy Plant at Chalk River, Ontario. After the war, Kirkbride took on senior management roles with CIL, ending his career in the late 1970s as Vice-President for Western Canada. Thus he never made his mark in soil mechanics. Yet David Kirkbride had introduced soil mechanics into the PFRA and opened the door for others.

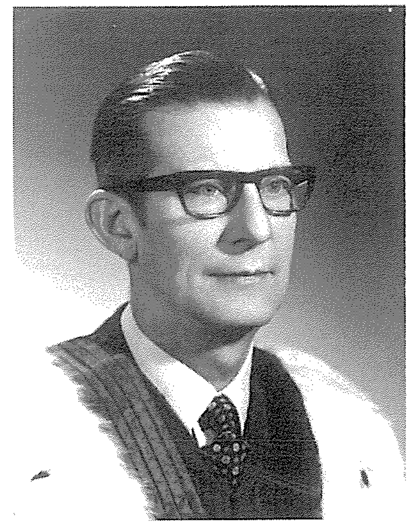
Robert (Bob) Peterson grew up on a farm near Plato, Saskatchewan, then completed high school in Saskatoon. He enrolled in the engineering college at the University of Saskatchewan in 1935, graduating with great distinction in 1939, when he joined the PFRA staff. Dean Mackenzie persuaded Peterson to take the Harvard graduate course in soil mechanics, which he undertook in 1940-1941.

After graduating with a master's degree, Peterson returned to the PFRA, where be became Chief Soil Mechanics and Materials Engineer. An agreement was made between the PFRA and the university to establish a laboratory in the Engineering Building on the Saskatoon campus. The lab was made available to the students and Peterson also lectured on soil mechanics.

PFRA's first major dams, Pothole and St. Mary, were designed by Peterson and built in southern Alberta. St. Mary, one of the largest earth dam projects undertaken up to that time, was a precedent-setting dam in Canada. The technical concern was the strength of a 200-foot-high embankment of which the principal ingredient was clay till. It was the first design based on the application of soil mechanics to the investigation of foundation and construction soils, the first in which quality control of water content and compaction density was maintained during construction, and the first in which significant instrumentation was placed to monitor the performance.

Charles Ripley, an Alberta and Harvard graduate, was Peterson's resident engineer on the project from the summer of 1946 through 1948. Ripley has pointed out that the initial problem faced by the early practitioners of soil mechanics was to gain the confidence of the civil engineers administrating the project. According to Ripley, Bob Peterson possessed a marvelous ability in precisely that capacity: "He got along well with the district engineers, and he made a great contribution in demonstrating that there was a place for soil mechanics in engineering of dams."

When the Travers Dam was constructed on a Bearpaw Shale foundation, Peterson was the first person to investigate the treacherous expansive properties of this material. Peterson's crowning achievement was the successful completion in 1967 of the Gardiner Dam on the South Saskatchewan River, also built on the Bearpaw Shale. Bob Peterson spent his entire career with the PFRA. He also worked as a specialist consultant on review boards and became internationally recognized as an authority on earth dams. He died untimely in 1969 at the age of 51.

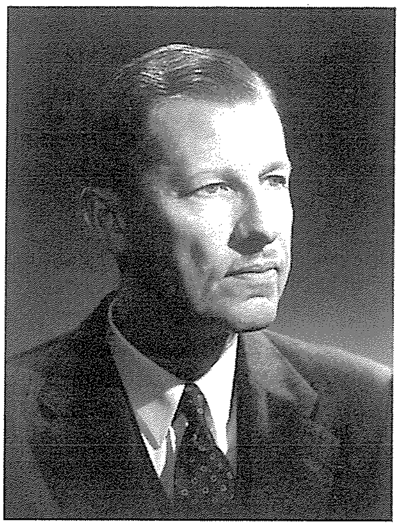


Jaques E. Hurtubise
École Polytechnique

Karl Terzaghi had laid the foundations for a strong soil mechanics school at MIT. Among his successors were professors Glennon Gilboy, who joined the faculty in 1926, and Donald W. Taylor in 1932. Both of these men died relatively young, but both left a lasting impact on soil mechanics. Taylor's textbook, *Fundamentals of Soil Mechanics*, published in 1948, was an outgrowth of the lecture notes prepared by Terzaghi and Gilboy at MIT and became a standard textbook in American soil mechanics schools.

Jacques E. Hurtubise (1911-1987), born in Montreal, earned his B.A. from the Jesuit College Ste. Marie in 1929, then entered the École Polytechnique of Montreal, where he received his civil engineering degree in 1934. Upon graduation, Hurtubise obtained a three-year teaching post, 1934-1937, at this school, followed by a two-year stint with a consulting firm. He returned to the École in 1939 to take charge of the materials testing laboratory.

Raymond Boucher, Professor of Hydraulics at École Polytechnique, had taken his master's degree in hydraulics in 1933 at MIT, where he had also attended a class in soil mechanics given by Professor Gilboy. As a result,



Raymond Boucher
École Polytechnique

Boucher recognized the need to set up a soil mechanics program at the École. When Hurtubise returned to the faculty in 1939, Boucher had his younger colleague take the intensive six-week soil mechanics course offered that summer by Professor Taylor at MIT. Thus in the 1939-1940 session, Boucher and Hurtubise worked together setting up lecture notes and a small soils laboratory, and instituted the first soil mechanics program in the province of Quebec. Hurtubise went on to become Director of the Civil Engineering Department at the École, and he continued to teach geotechnical engineering there until his retirement in 1977. Professor Hurtubise was involved as a soils consultant on such major projects as the Dorval Airport, 1941-1944, the St. Lawrence Seaway, 1953-1958, the construction of several hydroelectric dams with Shawnigan Engineering and Hydro-Quebec, and the Montreal Metro.

Robert F. Legget, C.C. (1904-1994), a native of Liverpool, England, obtained bachelor's and master's degrees in civil engineering from the University of Liverpool in 1925-1927. At Liverpool, honours engineering students took a minor in geology under the eminent Professor P.G.H. Boswell. The lectures and field work in geology kindled Legget's lifelong interest in this discipline and its interaction with civil engineering structures.

In the early spring of 1929, at the age of twenty-five, Bob Legget arrived in Montreal. In the United Kingdom, he had worked on the investigation and construction of a powerhouse and tunnel, and his first job in Canada was on the construction of a hydroelectric plant, where he had the opportunity to observe "the fundamental importance of geology in civil engineering, and especially the geology of soils," a subject which had been neglected in the technical literature. At the instigation of Dr. J.J. O'Neill, Professor of Geology at McGill University, in January 1934, Legget read a paper, "Geology and Civil Engineering: Their Relationship with Reference to Canada," before the Montreal Branch of the Engineering Institute of Canada. With the encouragement of his mentor Boswell, this led to the publication in 1939 of Legget's classic first book, *Geology and Engineering*, which included a chapter on "Soil and Soil Mechanics."

In 1932 Legget obtained employment as a technical advisor with the Canadian office of a British steel sheet-piling company, which brought him into contact with foundation conditions from the Atlantic provinces to the west of Winnipeg. Although not formally trained in soil mechanics, Legget had read Terzaghi's first American articles, published in *Engineering News-Record*. In the spring of 1936, in a short item in *ENR*, Legget read about a forthcoming conference to be held at Harvard University that June. Thus Legget came to attend the First International Conference on Soil Mechanics and Foundation Engineering. He contributed a report on the conference to the EIC's *Engineering Journal*. This avant-garde meeting of civil engineers from around the world inspired Legget to a change in career.

On his return home from the conference, Bob Legget decided on a teaching career. So he wrote to some ten engineering schools enquiring about a teaching post, but it was the depth of the Depression and all the responses were negative. Just as he had given up on the idea, Legget received a last-minute call from Queen's University, Kingston, which had an unexpectedly large enrollment that fall of 1936, and thus was offering him a lectureship in civil engineering. In 1937 Legget was assigned one room in the laboratory, and by early 1938, it was "equipped for the simple soil tests." However, by late summer of 1938, Legget received an appointment from C.R. Young, head of the Department of Civil Engineering at the University of Toronto and who had also attended the Harvard conference, as assistant and later associate professor, responsible for a course in foundations. Legget spent nine years at this institution, during which time he established its soil mechanics laboratory and took on various consulting geotechnical assignments on dam, mining, northern transportation, industrial, and building projects.

Canadian Organization

Robert Legget is widely regarded as the father of organized geotechnical engineering in Canada. Legget, in turn, has called C.J. Mackenzie, "the real founder of organized soil mechanics in Canada." Regardless of the question of firsts, both men worked hand in hand to set up the organizational structure in this field. In 1939 Dr. Mackenzie was co-opted from the University of Saskatchewan for the war effort, to become acting president of the National Research Council of Canada. He continued as president from 1944 to 1952, when he became first president of Atomic Energy of Canada Ltd.

On April 30, 1945 Mackenzie formed the NRC Associate Committee on Soil and Snow Mechanics (later called the Associate Committee on Geotechnical Research), which he asked Legget to chair. The committee's immediate "top-secret" job was to research, jointly with the United Kingdom and the United States, a problem being encountered by the tracked vehicles of the Allied Forces — they were bogging down in the "mud" of northern France. The name, chosen by Mackenzie, was somewhat of a camouflage, with snow added because of a projected winter invasion of Norway, in which Canadian troops would play a leading role. Beyond the wartime need, however, in establishing the committee the far-sighted Mackenzie foresaw that Canada would need a medium for the research and development of soil and snow mechanics, to meet for a great variety of peacetime problems.

At the Fifty-Ninth Annual General Professional Meeting of the Engineering Institute of Canada, held in Winnipeg in February 1945, for the first time a session was devoted to soil mechanics, co-chaired by Legget and A.E. Macdonald, professor of civil engineering at the University of Manitoba. Two papers were presented. One was by Robert Paterson on the investigation and design of the St. Mary Dam, which was a landmark paper on embankment design in Canada. The other was by Gerry B. Williams, materials engineer of the Manitoba Highways Branch, on the application of soil mechanics to the design and maintenance of Prairie Highways. By this time, highway laboratories of the various provincial highway departments were being equipped to identify and classify sub-base soils and for moisture and compaction control of construction. These papers were reported to have "aroused much interest and good discussion."

By the end of World War II, the validity of soil mechanics in civil engineering practice was proven beyond a doubt. The great post-war development of Canada began in the early 1950s and created a large demand for soil mechanics engineers in the building, industrial, and energy fields. As a result, soil mechanics programs were being instituted in all civil engineering schools across the country. With more engineers practicing in the field, the organizational and technical infrastructure of the profession also developed apace.

President Karl Terzaghi of the International Society for Soil Mechanics and Foundation Engineering called upon Robert Legget to organize a Canadian Section of ISSMFE and to be the Canadian delegate to the executive meeting to be held at the Second International Conference at Rotterdam in 1948. As a result, Legget, in his capacity as chairman of the Associate Committee, convened the first Canadian Civilian Soil Mechanics Conference in Ottawa on April 28-29, 1947. Legget opened and chaired the conference while C.J. Mackenzie expressed the welcome of NRC. L.F. Cooling, Head of the Soil Mechanics Section of the British Building Research Station, and his assistant G.G. Meyerhof were honoured guests. Forty "active workers in the field" attended, representing all the provinces except British Columbia. Most of the delegates were from the universities and government agencies, as there were then few private practitioners in the field. The individual delegates reported on their work. As well, an inventory was taken of the soil testing facilities then available in Canada. A subcommittee, comprising the chairman and six regional representatives, was struck to act as the Canadian National Committee at the Second International Conference. The Canadian conferences have continued annually in cities across the country with the Golden Jubilee Conference to be held in Ottawa on October 20-22, 1997.

Later in 1947, envisioning the postwar building boom in Canada, President Mackenzie established the NRC Division of Building Research, based on the earlier British model, with Legget as first director. The DBR acts as a catalyst for the universities, the design professions, and the construction industry in

Banquet, Sixth International Conference on Soil Mechanics and Foundation Engineering, Montreal, September 1965
Associate Committee on Soil and Snow Mechanics

simulating research in the building field. It also updates the National Building Code. The DBR soil mechanics research laboratory was established in early 1948 under the first research officer and secretary of the Associate Committee, F. Lionel Peckover, a former student of Legget at Toronto, who later took the Harvard soil mechanics course. Three principal areas of the division's research have pertained to geotechnical concerns: foundations and soils, snow and ice, and building problems on muskeg and permafrost in the Canadian North.

Canadian Geotechnical Society

By 1961 the Engineering Institute of Canada formed a Geotechnical Engineering Division to accommodate the rapid growth of the profession, now with many geotechnical consultants involved. At this time the nomenclature soil mechanics was falling into general disuse, being superseded by the more generic term geotechnical. The change came about because of the broadening of the discipline to include such allied fields as engineering geology, rock mechanics, hydrogeology, and geosynthetics. Membership numbers were now in the hundreds, far beyond the early small meetings of research workers. Therefore in 1961-1962 the EIC Geotechnical Engineering Division jointly sponsored the annual conferences and thereafter took full responsibility.

In September 1963 an ad- hoc committee in southern Ontario instigated publication of the *Canadian Geotechnical Journal* under the editorship of Victor Milligan. Initially independent, in 1969 it became one of the scientific journals published by the National Research Council of Canada and the principal publication medium for geotechnical papers in Canada.

A further milestone in Canadian geotechnical engineering took place on September 8-15, 1965, when Canada hosted the Sixth International Conference on Soil Mechanics and Foundation Engineering, held in Montreal. To plan the event, a Canadian Organizing Committee was established by the Associate Committee with Robert Legget as chairman and members selected from across the nation. Many others contributed to the success of this conference, which had 1,153 registrants from 53 countries around the globe. It demonstrated to the world that Canadian geotechnique had come of age.

An outgrowth of the conference was the beginning in 1963 of a newsletter to keep members of the Canadian Section of ISSMFE informed of the planning for the conference. This eventually evolved into the quarterly magazine, *Geotechnical News*. An interesting sidelight as well, was the selection of a conference symbol. The Organizing Committee held a competition and the winning design depicted a beaver on top of an earth dam, imposed upon a map of Canada. The beaver motif bears a striking resemblance to Sandford Fleming's design of the three-penny postage stamp of 1851. This conference symbol would become the logo of the Canadian Geotechnical Society.

Robert F. Legget, through his organizational skill, eloquent oratory, and prolific writing, was instrumental in establishing geotechnical engineering as an active and recognized learned society in Canada. On his retirement in 1969 as Director of the NRC Division of Building Research, his geotechnical colleagues instituted the R.F. Legget Award, "for excellence in the geotechnical discipline," which has become the highest annual award of the Canadian Geotechnical Society. Robert Peterson was the first recipient of the award, posthumously, in 1970, followed by Robert M. Hardy, in 1971.

In 1972 the Canadian Geotechnical Society was formed as a constituent society of the EIC. Thus the society became self-governing with its own board of directors. Geoffrey G. Meyerhof was elected as first president. In 1985 the society was federally incorporated as a financially independent body. The day-to-day affairs of the society are administered by a director general, who is responsible to the president and board. The affairs of the society are wide-ranging. It organizes and runs the annual conferences and publishes the proceedings. It also co-sponsors several specialty conferences. As an example, in June 1983 it hosted the Seventh Pan-American Conference on Soil Mechanics and Foundation Engineering, convened in Vancouver, on the theme, "Geotechnical Engineering in Resource Development." This marked the first time that a North American city hosted this conference. The society publishes "CGS News" as part of the quarterly magazine, *Geotechnical News*. It also publishes the respected *Canadian Foundation Engineering Manual*. The CGS also acts as an umbrella organization for the regional geotechnical societies that have sprung up in the major cities across the country. Fifty years after the modest initial meeting of the 40 geotechnical practitioners of soil mechanics, the Canadian Geotechnical Society has grown to a membership of over 1,400.

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CYRIL E. LEONOFF is a native of Winnipeg and a 1949 graduate in civil engineering of the University of Manitoba. He was a graduate research fellow of the Engineering Experiment Station, University of Washington, under Professor Robert G. Hennes, who had studied soil mechanics under Karl Terzaghi at MIT. After employment with Public Works of Canada, Rivers and Harbours Branch, Leonoff joined Ripley and Associates in 1952 and retired as executive vice-president of Klohn Leonoff Ltd. in 1985.

Leonoff is currently a researcher and writer and has authored a number of articles and books on historical topics. He has served the City of Vancouver as a member of the Planning Commission, Development Permit Advisory Panel, and has chaired the Vancouver Heritage Advisory Committee.

In 1995 he was recipient of the Community Service Award of the British Columbia Professional Engineers.

Professor I.F. Morrison

Harold L. Morrison

History is often recorded in terms of the lives of those who made it. So it is with the author's father. Professor I. F. Morrison. The following paragraphs may shed some light on the nature of the man and the role he played in 1937 by establishing soil mechanics as a distinct part of geotechnical engineering in Canada.

Professor I.F. Morrison.

Ibrahim Folinsbee Morrison was born February 9, 1889 in Braintree, Massachusetts, a town just south of Boston. He received his early education there and at Theyer Academy in Brookline, also a suburb of Boston. After two years at Dartmouth College, majoring in mathematics, he transferred to the Massachusetts Institute of Technology where he received a B.Sc. in Civil Engineering in 1911.

During this period he spent some of his summers working for C.F. Allen, a prominent surveyor in Boston and the author of Allen's Tables, which for years was the bible for survey calculations.

Academic

Morrison returned to M.I.T. as a lecturer for the 1911/12 session and then joined the University of Alberta as a lecturer in civil engineering in the fall of 1912. He taught the first class of engineering students at the university and probably every engineering graduate through 1956.

When the university suspended classes in 1916, my parents moved to New York City where my father took a position with Lockwood Greene, a consulting firm which continues today. In late 1917 he enlisted in the U.S. Army, was promoted to the rank of Lieutenant and posted to France with the Ordnance Corps. Upon his discharge in February 1919 he returned to the university, but for several years worked for Lockwood Greene during the summer months, specializing in reinforced concrete design. He became a Canadian citizen in 1935.

Morrison was appointed Professor of Applied Mechanics in 1922, the position which he held until retirement in 1954. He continued at the university as Professor Emeritus until his death in February, 1958. In 1953 the University awarded him an honorary doctor of laws degree.

University salaries were not large in the early years ($100 per month for seven months per year) and most members of the staff took other assignments during the summer break. In engineering this was essential to provide experience in the "art" of the profession, and it made a significant difference in his ability to make lectures interesting and relevant.

Professor Morrison was a quiet, almost humble person who was very patient and slow to anger. He was often annoyed by politicians or by people who were unable to reason in a logical fashion. He had the ability to make very cutting criticism of those he believed to be incompetent. (A May, 1942 letter to *The Engineering Journal* commenced, "In this paper there appears to be a certain amount of misunderstanding of fundamental facts...")

While he may be remembered by many for his very practical approach to the solution of engineering problems, his first love was always mathematics and one of his hobbies was the study of the theoretical aspects of the subject.

Possibly the best way to describe my father's reputation as a teacher is to quote from a talk by his student and colleague, Dr. George Ford, former Dean of Engineering, on the occasion of the 75th anniversary of the Faculty [1]

"Of all the appointments in engineering then or now, that of Professor Morrison has to be considered paramount. If it is the role of the undergraduate teacher to stimulate the intellectual zeal of students, then he was a teacher par excellence. What impressed most of those with whom he associated, was the curious power he had to stimulate the thinking of others. It was not honours students alone who found new delight in thinking. He fired the imagination of all.

Far more important than diplomas, are the minds thus stimulated! His profound insight on the methodology of design, the hallmark of engineering, left each of his students a richer person."

Professor Morrison believed vehemently that it was the duty of the senior members of the faculty to teach undergraduate courses and indeed he did so for his entire university career. He also taught graduate courses and was instrumental in establishing a policy that made many of them available to interested undergraduate students.

In a paper published in 1914 [2] he set out his basic philosophy of engineering and thus the way in which he believed it should be taught.

"It is the chief function of any engineer, young or old, to solve problems and to obtain not only a solution but the best solution from all points of view. Such a best solution requires a sound knowledge of the fundamental principles of physical, chemical and mathematical sciences and some understanding of business methods, economics, law and many other important fields."

A later statement in the same paper established his approach toward teaching of engineering subjects.

"One of the outstanding faults of the present-day engineering student is his dependence on problems and textbooks. The tendency is to bury the fundamentals in problems with the resulting loss of independence on the part of the student. Drill is for those who are followers, not for leaders. Problems should demand the application of principles and common sense rather than formulae. They should be interesting and practical."

This philosophy always crept into his lectures: if you are stuck on something you should go back to first principles. This was one of the most important things I ever learned from my father. In solving any sort of difficult problem, you can always break it down into its components and then look at each one in terms of basic principles. He also placed great emphasis on the significance of numbers and accuracy as distinguished from precision, a subject that is often neglected these days.

The remains of operation Habbakuk lie at the bottom of Patricia Lake. . . but as late as 1959 the report was still listed as "Most Secret".

The use of soil as a material and as a foundation has been of concern to civil engineers for centuries, but for years most analyses and studies were conducted on a purely mathematical basis. At the turn of the century engineers began to develop purely mathematical analyses of the way in which earth pressure and other phenomena develop. At the same time, studies were commenced on the engineering or physical properties of soils. In 1925 Dr. Karl Terzaghi brought all of these things together when he coined the term *Erdbaumechanik* to describe the study of soil and soil mass in terms of its properties. In the same year he provided the official translation as "soil mechanics," a title which was not quickly accepted as a separate area of study in the English-speaking world. But, the professor of applied mechanics was attracted to it! My father had taught himself to read German and subscribed to a number of German periodicals. Throughout his lifetime he translated technical papers including those of Terzaghi and Muller.

In 1925 the University of Alberta recognized "Foundations" as a separate subject in the fourth-year civil engineering curriculum and required a course in applied mechanics as a prerequisite. It was not until 1931 that the "Foundations" course included a segment separately identified as soil mechanics. In the previous year, a soils laboratory had been introduced. It consisted of one session on sample preparation and seven "experiments" which were all simple classification tests, much as they are performed today. This followed the general trend that was to consider soil mechanics as simply a part of foundation or earthwork engineering.

The First International Conference on Soil Mechanics and Foundation Engineering was held at Harvard University in June 1936 and professor I.F. Morrison was one of eight Canadians who attended. This may have been the start of a lifelong friendship with Dr. Robert F. Legget who was also a delegate.

In 1937, the University set a precedent in Canada when the fourth year course on Foundations was renamed "Soil Mechanics and Foundations," with the instructor listed as Professor Morrison. Other Canadian universities did not quickly follow this move and in 1940 there was still a debate as to whether or not soil mechanics should even be considered suitable for undergraduate study[3]. In 1942 a completely separate course on soil mechanics was introduced into the third-year civil engineering program.

Professor Morrison's attitude towards site investigations was set out in a 1939 paper[4], "Without data as to the depth and character of the various subsoil strata, the rational design of foundations is impossible." Consequently, for many years, undergraduate students were given practical experience through undertaking investigations and studies for actual projects. One such assignment involved the foundation for a new stack at the University Power Plant. It was to be almost identical to an existing stack and reasonably close to it. After completing the field and laboratory work, the class produced a settlement estimate for the new stack. My father, who was designing the stack, immediately declared that it was wrong and a very lively discussion ensued. He won the day by pointing out that in over twenty years, the existing stack had settled considerably less than one half of the calculated amount. In this way, many of the students learned one practical aspect of foundation engineering, which is to examine other, nearby structures to see how they have performed.

Robert M. Hardy joined the staff of the Faculty of Engineering in 1930 and became a very close friend of our whole family. It was at my father's urging that he spent the 1939/40 session studying soil mechanics at the Harvard Graduate School of Engineering. In 1946 the teaching of Soil Mechanics was turned over to Hardy, who continued to emphasize the importance of understanding the fundamental principles of soil behavior as a basis for foundation and earthwork engineering.

While my father continued to teach undergraduate and graduate courses on foundations, his major interest returned to structural engineering and the strength of materials. Most of his research activities were in these areas and over half of his published papers dealt with structural analysis or structural materials. In 1937 he consolidated his lecture notes and other material into a textbook[5] which was later enlarged and reprinted on several occasions.

In 1951 he was appointed to the Technical Committee on Design for the National Building Code and also spent a significant amount of time on revisions to the foundations part of the Code.

Research

Several research activities are of interest. The first was an attempt to design and build a pressure cell for the measurement of earth pressure. It was based upon the use of a vibrating wire with an arrangement to measure the vibration frequency and thus the stress in the wire and load on the movable plate of the cell. While the laboratory tests of the apparatus were promising and several papers were published, there is no evidence that the cell was ever used or that it would perform in a full-scale installation[6].

Another research project related to the use of ice as a building material. In 1942 at the height of the Battle of the Atlantic, an English physicist by the name of Geoffrey Pyke, suggested the construction of an ice aircraft carrier to enable air support for North Atlantic Convoys[7]. Preliminary research and design for this project were assigned to the National Research Council of Canada and my father was one of several engineers asked to study the properties of ice and reinforced ice. This involved tests on cubes and cylinders of ice made in different ways. Subsequently, he load tested a number of ice beams, reinforced with a wide variety of materials. In the end, wood fibres seemed to provide the best way to strengthen these members. This had originally been proposed by Pyke and the mixture was referred to as Pykrete.

Larger scale tests on columns and beams were made on ice taken from Patricia Lake, near Jasper, Alberta. Other sections were carved from ice in the Columbia Ice Fields, 70 kilometres to the south. These were load tested and later a number were tested for resistance to explosives.

A model of the ice aircraft carrier was built in Patricia Lake. It attracted a lot of attention, but in the end it was determined that construction of the full-scale carrier would take too long. The remains of operation Habbakuk lie at the bottom of Patricia Lake. There is now a cairn to describe the project, but as late as 1959 the report was still listed as "Most Secret."

This interest in the properties of ice led to extensive analytical and laboratory research into the problem of how thick an ice layer is required on a northern lake to permit the safe landing of large aircraft. Closely related to this was significant research into the stresses that surround holes in thin plates of all sorts.

Consulting

Consulting on engineering matters was an important aspect in the life of any faculty member. Over his lifetime my father opened in excess of two hundred consulting files, the majority of which were in the area we now describe as forensic engineering. He personally conducted dozens of foundation investigations for buildings and structures in and around Edmonton. Test pits, usually dug by hand, were a common feature of these studies. He was strongly against the use of wash-boring techniques to obtain samples. Dry augers were used on occasion and for one investigation in 1950 the drilling of four deep test holes in till took almost a month. The investigation revealed a very difficult foundation situation, which lead to the use of Franki piles, probably their first application in Western Canada.

An examination of some of the consulting files gives an insight into the way in which geotechnical engineering was practiced in the first half of the century. In 1926 he was retained by the City of Edmonton to assist in the design of the 109th Street Subway (locally known as "the rat hole") which was a facility to take the street under the main yard of the Canadian National Railways in downtown Edmonton. The determination was made that a buried, three-hinged concrete arch would be a less costly structure than the traditional railway bridge, but the railway was adamantly against this innovation. The correspondence shows that the railway engineers (in eastern Canada) did everything in their power to discredit the arch design and the allowable soil-bearing pressure became a major issue. Each side quoted various textbook references for an allowable bearing pressure on a "stiff gray clay." The railway wanted a maximum of 4,000 p.s.f while the City hoped to use 6,000.

Another consulting file relates to an early experience with perennially frozen ground. The term "permafrost" was not introduced until 1945. . .

Also, the railway insisted that the foundation loading include the impact from two heavy locomotives travelling at speed. To resolve the impasse my father undertook a load test at the appropriate depth. A plate with an area of two square feet was incrementally loaded and the settlements measured. At a total load of 18,480 pounds the settlement was 0.02 feet. On this basis it was agreed that a bearing pressure of 6,000 p.s.f. was acceptable, but the design loading still had to include the impact load. Although several of the other conventional underpasses in the area have required major repairs over the years this structure has stood up remarkably well.

Another consulting file relates to an early experience with perennially frozen ground. The term "permafrost" was not introduced until 1945 but in 1941 my father was asked to provide advice concerning a house which had settled due to thawing of frozen ground. The previous year the Hudson's Bay Company had decided to improve the living accommodation for its northern managers by building new houses. The first was a six-room, 24 ft. by 32 ft., two-storey house in Yellowknife, N.W.T. It had a seven-foot-deep basement containing a wood-burning furnace near the northwest corner. The basement walls consisted of horizontal 2 x 8 V-groove wooden planks on timber frames which were supported by 24-inch-square concrete footings. There were three interior columns also supported on square footings.

A young geologist who was going to Yellowknife on other business was retained by my father to undertake a site investigation. He reported that the soil profile was 18 to 30 inches of sand underlain by firm gray clay. At the foundation level the clay was very soft and wet. He had difficulty in keeping the test holes open but found that the frost line beneath the house was some five and one half feet below the concrete basement floor.

Surface drainage was good and clearly the loss of heat from the house had caused the frozen ground to thaw. The northwest corner of the house had settled about twelve inches, the furnace had settled at least two and one half feet, but the south and east sides of the house had moved very little.

There were two recommendations made at that time. The first was to move the house and rebuild it without a basement. If moving was not practical, the alternative was to install timber or precast concrete piles below the house and furnace. The piles were to be placed in drilled and cased holes and were to extend at least six feet into the frozen ground.

Moving the house was not acceptable to the HBC and the file does not indicate if the second recommendation was implemented. (The total consulting fee, including payment to the geologist was $37.50.) In any event, by 1944 the basement walls had been pushed in, possibly by frost action, and a second opinion was sought. At that time a recommendation to fill the basement and replace it with an 18-inch, coarse gravel pad was accepted. The furnace was relocated to a separate structure.

In 1928 my father commenced a long and interesting association with Montreal Engineering and Calgary Power Ltd. (now TransAlta Utilities Corporation) in the design and construction of hydroelectric facilities, power plants and other structures in Alberta.

The first project was the Ghost Plant, on the Bow River near Cochrane, in which his main interest was the concrete spillway and powerhouse. In 1940 he was heavily involved in the design of the earth fill, Lake Minnewanka Dam and the Cascade Power Plant, near Banff. In 1948 he took a major part in the design of the Three Sisters project, near Canmore, including the earth fill dam, canal and penstock. Apart from his role as a teacher, he looked upon these projects as some of his most interesting work. When he died in 1958 his ashes were scattered in the Bow River, the subject of some of his greatest professional achievements.

Notes

(1)Ford. G., 1988, *Sons of Martha: University of Alberta Faculty of Engineering 1913-1988*, Faculty of Engineering. University of Alberta.

(2)Morrison. I.F., "Possible Faults in our Methods of Teaching." *The Canadian Engineer*, Vol. 27.

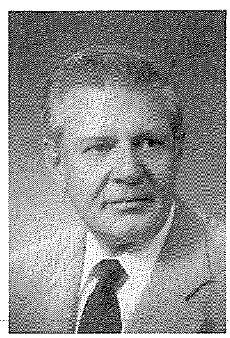
(3)Legget, Robert F., *The Place of Soil Mechanics in the Undergraduate Curriculum.* July 1940.

(4)Morrison, I.F., "Fundamentals of Pile Foundations." *Engineering Journal*, vol. 22.

(5)Morrison, I.F., 1937. Notes on the Science of Solid Materials, Edmonton Institute Press.

(6)Morrison, I.F. and Cornish, W.E., 1939. "Description of a Pressure Cell for the Measurement of Earth Pressure." *Canadian Journal of Research.*

(7)Lampe, David, 1959 Pyke, *The Unknown Genius*, Evans Brothers Limited, London.



HAROLD L. MORRISON, the son of Professor I. F. Morrison, was raised in Edmonton, Alberta and graduated in 1950 from the University of Alberta with a B.Sc. in civil engineering.

Originally with Brown and Root, a large engineering and construction organization, he became chief construction engineer in 1958. In 1963 he joined R.M. Hardy & Associates Ltd., an Edmonton-based geotechnical consulting engineering firm, as manager, and in 1975 was appointed president and C.E.O. Between 1963 and 1982 the company grew from a total staff of 30 to nearly 700, with offices across Canada.

Mr. Morrison retired from the firm in 1986 and established a practice in dispute resolution. He has also been heavily involved in community and professional activities.

Robert Macdonald Hardy
Engineer, Consultant, Teacher

Murray C. Harris

Robert Macdonald "Bob" Hardy was not a tall man, yet he had a presence that stood out in a crowd. He always wore a suit and until his last few years was never without his cigar and enormous cup of coffee. On his 75th birthday he was cut down to one cigar a day and promptly went out and bought a hundred. He died at the age of 79 years after 50 years of active engineering, consulting and teaching the length of time we are now celebrating as a society.

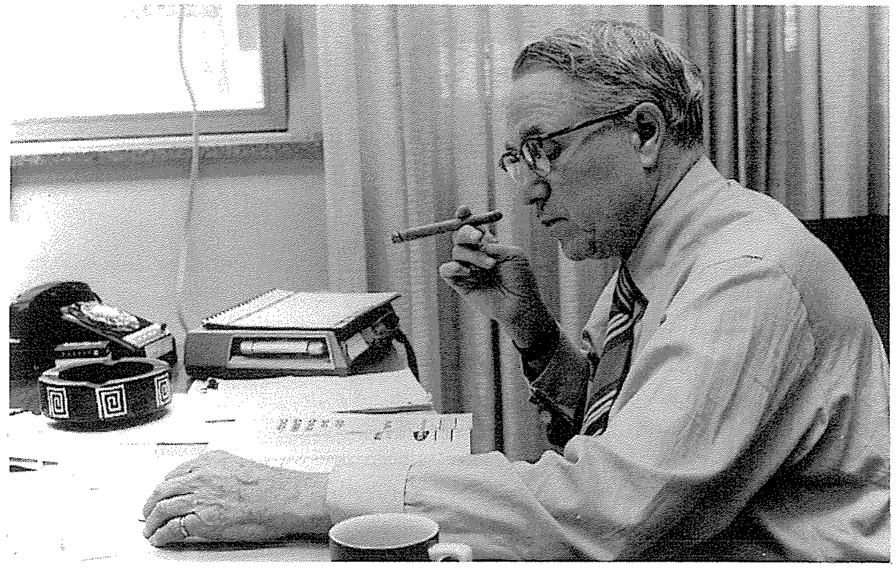


Fig. 1. Dr. Hardy at his desk at the University of Alberta, 1971. Courtesy University of Alberta Archives

The cigar was his trademark, (Fig. 1) and his careful attention to finding one, trimming the end (with the same knife that was calibrated in tons per square foot) and lovingly lighting it up, bought him a minute or two to gather his thoughts for the answer to a tough question.

This shy gentle-voiced engineer, earned the title of "Doctor" three times, yet never completed a doctoral graduate course. The title "Doctor" was never grudgingly given and many a construction superintendent or foreman would mention what the "Doctor" (no need for last names) told him. His own salutation over the telephone was "This is Bob Hardy, could you ...?" No "how are you," or extraneous conversation, but right to the heart of the matter. Courteous and polite, impersonal and pragmatic, gentle and tough, he was not easily crossed but great to work for.

Bob Hardy graduated with a gold medal in Civil Engineering in 1929 and a year later completed his Master's degree in Structural Engineering at McGill University in Montreal. Two years prior he had successfully completed the exams for Dominion Land Surveyor, no doubt as insurance for summer or permanent works in those days of recession.

Although his early days included work as a draftsman and surveyor, Bob Hardy was, from 1930 on, always associated with university life as student, teacher or administrator. In the summers of 1933 and 1934 he followed his initial bent as a structural engineer, taking post-graduate courses from Timoshenko at the University of Michigan. However under the influence of Professor I.F. Morrison, who gave the first course in soil engineering in Canada, he soon turned to that discipline for his life-long interest.

Bob Hardy joined the University of Alberta as a sessional lecturer in September 1930. By means of a mild threat that he had a job offer in industry (Canadian Industries Limited), his rank was raised from Lecturer to Associate Professor in the Department of Civil Engineering on 1 September 1937 at an annual salary of $2,500 (he was considered a "valued instructor"). He took his one sabbatical in 1939-1940 to take post-graduate study in Soil Mechanics at Harvard under Arthur Casagrande, and established a working relationship with him that lasted throughout their careers. He did not finish the necessary graduate work for his doctorate, apparently because of his marriage in August 1939 or because of the newly started war in Europe. He had joined the Canadian Reserve Army in 1938 and achieved Captain's rank in 1941. He did, however, find time to write a paper for the first conference on Soil Mechanics at Purdue in 1940 (anisotropy revealed by triaxial testing on flax grains).

The later part of the war years saw an increased interest in geotechnical engineering to serve the airports being constructed or refurbished in the north. Bob Hardy was at the forefront of the Canadian research on permafrost, and he and Elio D'Appolonia received the Kiefer Medal from the Engineering Institute of Canada for their paper, "Permanently

Frozen Ground and Foundation Design," published in 1946.

1946 was the year that Hardy became the Head of the Department of Civil Engineering, a full professor and acting Dean of the Faculty of Engineering. A year later he became permanent dean, a post he held until 1959 when he "retired" to devote full time to his consulting practice, albeit still as a part-time professor. It seems that he got into full swing at this time, organizing graduate students programs, fostering research (a member of the Alberta Research Council from 1948 onwards), member of the Council of Association of Professional Engineers, Geologists and Geophysicists of Alberta, and then President (1949 to 1950) and, not least, forming his own consulting firm in 1951.

Like most of those who pioneered soil mechanics (now geotechnical engineering) Bob's background was in an allied field: structural engineering. He was never daunted by problems linked to or associated with structures. In fact, he wasn't daunted by any problem in civil engineering and would apply the same methodical techniques to the design of a river groin, a dragline mining plan, or a sheet pile wall as he would to a dam or foundation always seeking specialist advice when he felt the need to focus on the problem his client needed solving.

Dr. Hardy was fond of the word "concepts." Few reports or papers did not contain that word somewhere, often accompanied by the adjective "modern." The word was symbolic of his approach place the problem in a scientific framework; teach the reader the solution to the problem. His reports were frequently addressed to those in relatively senior management positions who probably only wanted to know the "bottom line," but Dr. Hardy wanted them to know the facts behind and the rationale for the choices to be made. When it was suggested that perhaps he could write an executive summary for a particularly long report he said: "If I have to spend all this time preparing the report they have to spend the time to read it." By "time" he usually meant evenings or weekends; the balance of the week spent at teaching/administration. Hardy was called a full-time dean. A part time

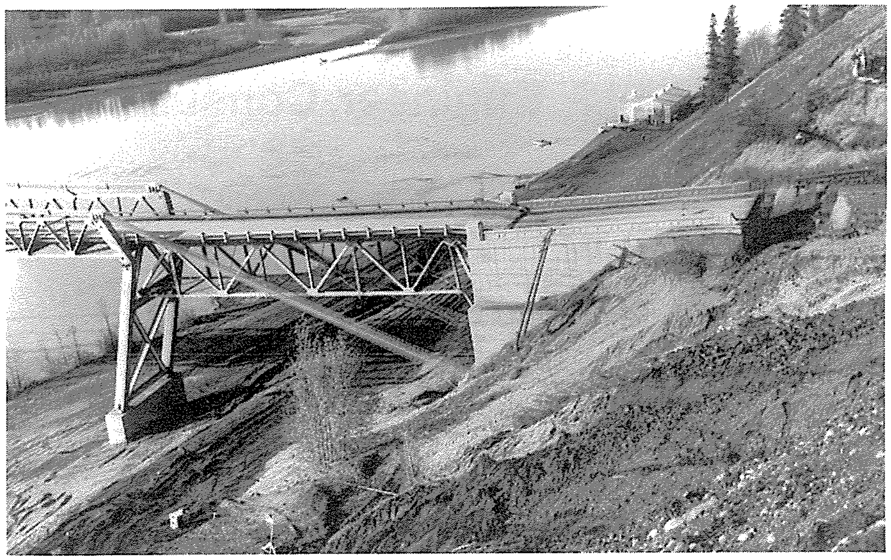


Fig. 2. Collapse of Peace River highway bridge at Taylor B.C. on 16 October 1957.
Courtesy University of Alberta Archives

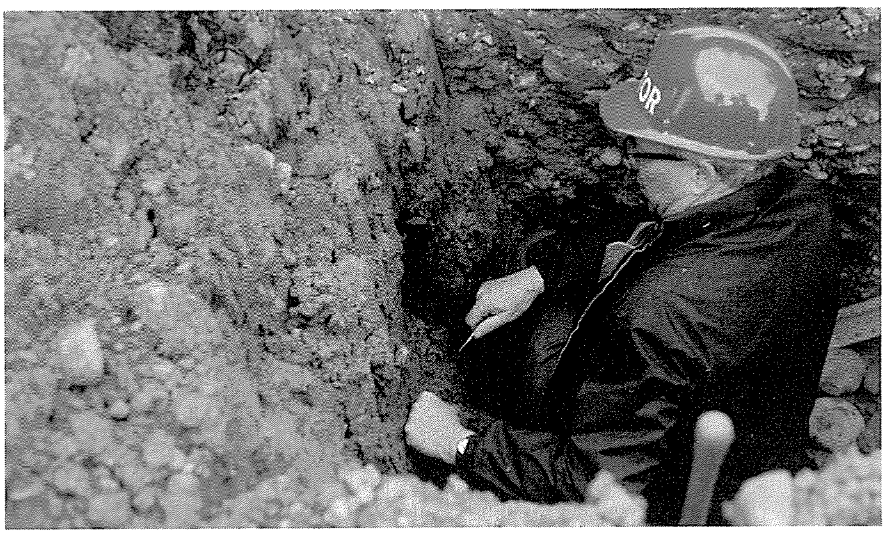


Fig. 3. Bob with the calibrated knife, examining core material at Big Horn Dam, 1971. MCH Photo

Fig. 4. "This is what happens, Scotty", Shell Test Pit in oil sand, 4 July 1975.
MCH Photo

dean spent part of his time as a dean and part time in consulting; a full-time dean spent all his time in consulting!

It might be misconstrued that consulting was a means to financial reward for the dean. On the contrary his "consulting" was as often as not attending a conference to present a paper, activities related to his profession (such as President of the Dominion Council of Engineers), or one of the many commissions that he was appointed to, such as the Borden Royal Commission on Energy in 1958, or the Manning Royal Commission on "Location of Pine Point Railway," in 1959. For these and many other services to community and country he received (among others) the Centennial Medal (Government of Canada), Centennial Award (Association of Professional Engineers of Alberta, 1968), RF Legget Award (Canadian Geotechnical Society, 1971), Officer of the Order of Canada (1974), and the Alberta Achievement Award (Province of Alberta, 1974).

Hardy's ability to handle many jobs at once is summarized by George Ford in the book, *Sons of Martha* -

"Hardy could talk to a staff member, plot a graph, read an article, answer the telephone, write a letter, and effectively deal with the problem at hand all at one time."

He always had some report or article with him on his many business trips (some 150,000 miles per year at one time) and would spend time in airports and hotel rooms writing letters or reports on the most recent job or problem. He used the dodge of many an administrator"I'll take it with me and let you know when I return." His office consisted of a large desk fronting on an even larger table. His filing system was to stack drawings, test hole logs and correspondence in piles, often with the most pressing jobs closest. His reply to phoned entreaties for a letter or report was something like: "I have the job right here in front of me and will get at it today." George Ford (Ford, 1988) said that ". . . if you wished to talk to him, you had to drive him to the airport."

In keeping with the tradition in civil engineering departments, research sought solutions to regional problems. Dr. Hardy and his co-workers encouraged and directed research in the areas of muskeg behaviour, frost action and its prevention, swelling clay and clay shale, oil sand and pile behaviour. Hardy quickly applied the results of this research, and that appearing in the literature, to the problems surfacing in his consulting practice. He first formed Engineering & Construction Services Ltd. together with Professor L. A. Chick Thorssen on 30 April 1951. Thorssen specialized in concrete, but left the firm in 1953 to work for a large contracting firm. In March 1954 the company was renamed R. M. Hardy & Associates Ltd.

Table 1 - Early Hardy Papers

Title	Publication	Date
Soil Mechanics Applied to Dams	*Roads and Bridges*	Oct 1945
Foundation Conditions in the Edmonton Area	2nd International Conference on Soil Mechanics and Foundation Engineering	1948
Low Cost Pavements	Civic Administration	Sept 1949
The Compaction of Soils	30th Annual Conv. Canadian Good Roads Assn.	Sept 1949
Construction Problems in Silty Soils	*Engineering Journal*	1950
Engineering Education and the Employer	Panel discussion *Engineering Journal*	1950
Stress Distribution Below Pavements Under Trolley Bus Loadings (with Phil Rivard)	Highway Research Board	1950
Prevention of Frost Heaving by Injection of Spent Sulphite Liquor	3rd. International Conference on Soil Mechanics and Foundation Engineering	1953
Foundation Investigation for the Kitimat Smelter (with Charley Ripley)	*Engineering Journal*	Nov 1954
Diagnosis and Treatment of Slide Conditions Affecting Highway	Canadian Good Roads Association	1955
Measurement of the Shearing Srength of Muskeg (with Stan Thomson)	Proc. Eastern Musket Research Meeting, NRC	Oct 1956
Discussion, Symposium on Frost Action	Proc. 38th Anual Convention, Canadian Good Roads Assn.	1957

Examples of the broad range of Hardy's interests in the early forties and fifties, and of the work being done at the university, are revealed by his papers of the period listed in Table 1.

One of the early by-products of the oil industry was the need for pipelines, particularly big-inch lines to carry gas and oil to other provinces and the USA.

In the fifties Hardy advised both TransMountain and Westcoast Transmission on location and facilities for their trunk oil and gas pipelines. He maintained his relationship with Westcoast Transmission, carrying out an annual inspection of all river crossings until failing health made it impossible.

He pioneered the use of a portable dictaphone on one of those field trips - portable only for a strong person but the

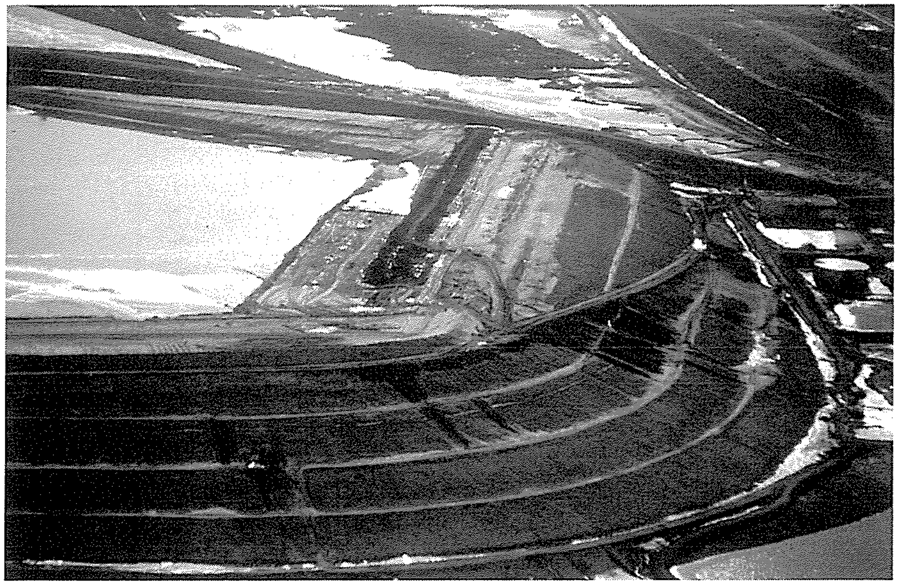


Fig. 5. Tar Island Dyke - north-east corner of tailings pond constructed mainly of hydraulically placed sand, 8 April 1976. MCH Photo

Fig. 6. R.M. Hardy & Associates Ltd. Annual Meeting 1972—Chairman Bob explaining the next course of action to (left to right) Jack Clark, Keith Goodman and Harold Morrison).

quality of speech from a quiet-spoken man over the roar of a helicopter was such that even knowledgeable interpretation by an engineer was hopeless.

In 1957 the University of Manitoba, for "work in the field of soil mechanics and foundation engineering" awarded Bob Hardy the first of his three honorary Doctorates, D.Sc. So far he had dealt only with plant and building foundations, strength of muskeg, building on permafrost, earth dams, dredged clay slopes and pipelines, was Dean of Engineering and head of a well respected consulting company. Time to get busy and do something.

On 16 October 1957 the Alaska Highway suspension bridge over the Peace River at Taylor, British Columbia collapsed following the wettest summer on record for many years (Figure 2). This was the first of many failures of large structures that Bob Hardy investigated, in this case for the owner of an adjacent pipeline suspension bridge, also founded on clay shale. From this and other work he and his colleagues developed a theory that for over-consolidated clay shales the conventional effective stress strength equations needed to be modified to include a term for swelling pressure in addition to pore pressure to account for the sliding failure process. While this theory is not widely held today, see however Chatterji & Morgenstern (1989), it is an example of an enquiring mind using the latest technology as it came along.

His method of investigating a new problem or a failure was to visit the site, examine the soil in detail, Fig. 3 review the available information, order exploration, instrumentation and testing, and then proceed to digest the data. This is where the 7-day week, 9-hour day helped. He would always plot the data and perform simple calculations based on basic soil engineering "concepts." Then he would mull things over, discuss the matter with colleagues, and give his unequivocal opinion and advice. He was meticulous in his plotting of data and conscious that outlier points often were the best data, not to be ignored or discarded. He was an early advocate of the slope indicator for movement observations and, following advice from Stanley Wilson, used the change of slope rather than the absolute movement as the best guide to interpretation.

In his lecture on the failure of the UGG grain elevator in Thunder Bay on 26 September 1959 (Thomson, 1962), a case where early plotting of data would possibly have averted a $2 million repair, Hardy said that an expert tends to explain a failure in terms of the field he (she) knows instead of looking over other fields. The UGG grain elevator, about which he went into structural design in great detail, was a good example of this situation. It was an advantage that he was initially a structural engineer, but he applied this advice to all his projects. In the case of the test pit in oil sand for Shell Canada Ltd. in 1974, he prepared detailed sketches of the dragline excavation plan and geometry to ensure that the proposed safe slopes in the overburden and oil sand and the reject piles would

Fig. 7. Excavation for Oxford Tower, (McCauley Plaza), Edmonton, 17 October 1968.

Fig. 8. Nearly completed Oxford Tower, (McCauley Plaza), Edmonton, 25 October 1968.

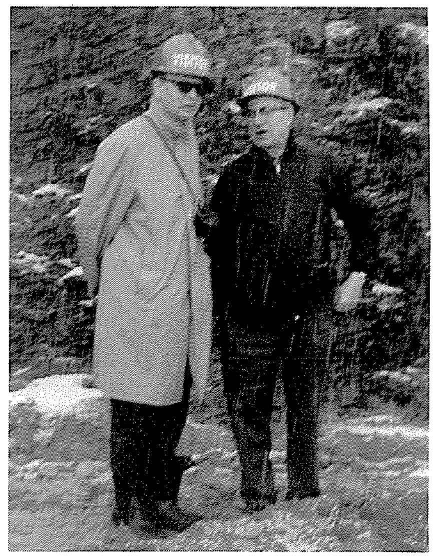


Fig. 9. Bob Hardy and Arthur Casagrande at Big Horn Dam, Alberta, 1971.

be feasible for the specific dragline being considered.

Hardy's involvement with oil sand (tar sand) in those days started with early work for the predecessor of Syncrude Canada Ltd. in 1959 and culminated with his Cross-Canada Lecture in late 1975. He was on the Review Board for Syncrude from 1974 to 1981. He wrote a series of reports on the behaviour of oil sand in 1964 that were characteristic of his approach to soil mechanics: detail the problem, present the data, put forth the necessary theoretical principles with worked examples, and give unequivocal advice or design parameters. He became a champion of the "four-phase" soil system in which gases dissolved in the water and oil in the pores played a significant role in the behaviour of the oil sand. Figure 4 shows Hardy explaining this concept to "Scotty" at the Shell Test Pit. Scotty in turn told Hardy that the pit wall would not fail as long as the dragline was sitting on it!

A major problem with the oil sand mining projects was disposal of the sand after removing the oil. At the first plant, GCOS (now Suncor), a containment pond was built using a small starter dam immediately adjacent to the Athabasca RiverTar Island Dyke. The starter dyke was originally 12 m high and built on up to 16 m of soft clay. Originally intended only to be made of clay, it was soon found that more storage was required and the dyke would have to be raised by the use of tailings as a construction material. What began as a relatively simple concept in 1964 soon turned into a major engineering structure, eventually 92 m high (Morsey et al. 1996). Figure 5 shows how the structure has grown. A respected geotechnical engineer reviewing the project described Hardy as "... one of the greatest civil engineers, or luckiest." The design grew as data became available, but one of the early successes was the way in which the sand tailings were deposited from the pipeline by spigotting to produce a relatively dense deposit for the shell of the dyke.

This spigotting technique for mine tailings was transferred to construction of the dykes at Griffith Mine and proved eminently satisfactory for construction of the dyke to retain Red Lake. The slopes of the tailings dyke were so flat that there was no question of bearing capacity failure on the soft clay even

Fig. 10. North-east corner of GCOS tailings pond looking south west, 8 April 1976.

when clay till and rock fill were placed on top to form the impermeable barrier and wave erosion control.

On his second retirement as Dean in 1971, after 41 years of service at the university, an *Edmonton Journal* reporter asked Hardy what his most important accomplishment was.

He didn't hesitate. "It would have to be the influence I've had on engineering graduates over a long period."

His influence was over more than graduates—many executives, superintendents and foremen learned from him and swore by him: "What the Doctor had said," was passed on to their staff, to disregard at their peril. One contracting company insisted that he or his company before construction started review all their river cofferdams.

In 1977 the University of Alberta, at the Fall Convocation, bestowed on Bob Hardy the honorary degree of Doctor of Laws. It meant a great deal to him, and it was a sign of his modesty that his address included the comment that he was now ". . . able to talk on an equal footing with so many of my former students who are now alumni of this university. . "! His Convocation Address of 17 November 1977 made many references to "the second mile," ("Whosoever shall compel thee to go one mile-go with him twain.") and closed with the following words that sum up his philosophy:

"As Wickenden (1941) said, 'Every calling has its mile of compulsion, its daily round of tasks and duties, its standard of honest craftsmanship, its code of personal relationships, but beyond these lies the mile of voluntary effort, the striving for excellence, unrequited service to the common good, and the desire to invest enduring significance to one's efforts.' He continued, 'It is only in this second mile that a calling may attain to the dignity and the distinction of a profession.' In the Engineering profession this text has stood the test of time, and still emerges as a living reality despite the increased complexities and sophistication of today's society. I commend it to you individually as a guide for your professional efforts as you continue on your chosen path, irrespective of how rocky this may be.

May it serve you well!"

Acknowledgements

Staff of the University of Alberta Archives were extremely courteous and helpful in providing access to the records of Dr. Hardy. Thanks are due to friends and colleagues of Dr. Hardy who shared anecdotes and memorabilia of him and which, even if not incorporated herein, brought back memory of an intense, warm and profoundly knowledgeable engineer. Of special mention are Harold Morrison and Stan Thomson who had much to do with the archiving of Hardy's records. Jack Mollard's (Mollard, 1987) notes on Dr. Hardy, which accompanied the first R.M. Hardy Keynote Address to the Canadian Geotechnical Society's Annual Meeting, contain many fascinating recollections of Bob Hardy.

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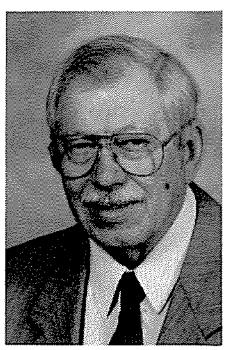

MURRAY C. HARRIS, was born in Cranbrook, B.C. In 1953 he graduated in civil engineering from the University of British Columbia. He later took graduate training in geotechnical engineering at the University of Alberta.

Harris's early engineering experience was with Canadian Pacific Railway, Underwood McLellan, and International Power and Engineering on the design and construction of the W.A.C. Bennett Dam, Peace River. In 1967 Harris became chief engineer at R.M. Hardy and Associates, where he consulted on major geotechnical engineering assignments for process and utility plants, dams, oil sands, and hydroelectric projects.

In 1978 Harris joined Thurber Consultants in Edmonton as chief engineer for Alberta, where he has been review principal for a wide variety of projects. He has served as director, president, and chairman of the Thurber Group, for which he is presently a specialist consultant.

Mr. Harris was co-founder and a president of the Geotechnical Society of Edmonton. He has been an associate editor of the *Canadian Geotechnical Journal*, has co-authored papers on oil sands, pipelines, permafrost, and pilings, and is the recipient of several honours and awards.

Robert Peterson and the Prairie Farm Rehabilitation Administration

Nickolai (Nick) Peters

Canada's Centennial Year was a time for celebrating, and so it seemed appropriate to celebrate the opening of Gardiner Dam on July 21, 1967. A crowd of 15,000 had come to see and hear Prime Minister Lester B. Pearson and other dignitaries. They were greatly impressed with the statistics of the mighty dam[1]: a 65-metre-high earth embankment containing 65,000,000 cubic metres of material, and a 225-kilometre-long reservoir in the middle of the drought-plagued Prairie.

Photo 1. Robert Peterson, PFRA Chief Soil Mechanics and Meterials Engineer 1941-1969.

The visitors stopped at the 5 tunnel outlets to feel the surge of the water as it churned past them. They marvelled at the massive concrete chute spillway with a capacity of 7,500 cubic metres per second, and they gazed in awe at the sentinel-like control towers. Then as they drove along the 5-kilometre-long crest they noted the gentle slopes that seemed to blend naturally into the abutments. Some even commented on the rough slump topography on the downstream valley slopes. However, most of them were oblivious of the fact that unusually large movements of 2.5 metres had taken place in the foundation, and that state-of-the-art geotechnical knowledge[2] had been used to successfully complete this dam. They also had not heard of the engineer, Mr. Robert Peterson, responsible for developing and applying this knowledge. Robert Peterson was somewhere in the background with honored guests, including a member of the Gardiner family, carefully explaining the basic points in earth-dam design. The safe construction of Gardiner Dam was a top priority in his professional life.

Robert Peterson grew up on a farm near Plato, Saskatchewan. His parents, of Norwegian and Irish descent, had moved to the Canadian West from the USA to brave the drought, the hailstorms and the vagaries of the Prairie weather. Peterson received his elementary schooling and part of his high school education in Plato. He completed high school in Saskatoon where he graduated with "distinction" in 1935. He then enrolled in the Engineering College at the University of Saskatchewan and graduated with a B.Sc. in Engineering, with "great distinction" in 1939.

After graduation Peterson joined the Prairie Farm Rehabilitation Administration. This was a federal government agency established in 1935 to find ways and means of overcoming drought conditions on the Canadian Prairies. They were primarily concerned with soil and water conservation.

Peterson's interest in soil mechanics was aroused during the first year of work with the PFRA. He then continued on to Harvard University where he studied under Dr. Karl Terzhagi and Dr. Arthur Casagrande. He received his master of science degree in civil engineering in 1941.

The Beginning

On his return to the PFRA, Peterson became Chief Soil Mechanics and Materials Engineer for that agency. He was one of the first engineers designated as a Soil Mechanics Engineer for a Canadian agency engaged in building dams. A joint agreement was drawn up between the University of Saskatchewan and the PFRA, whereby the University provided 50 square metres of space in the Engineering Building and the PFRA supplied the equipment for a modest laboratory. The equipment was available for the students in their soil mechanics studies. Peterson also gave a series of lectures on soil mechanics.

One engineer and three technicians were responsible for all the PFRA soil testing.[3] A few seasonal employees were hired during the summer to assist in the field investigations. Drilling and sampling were done by means of hand auguring, washboring, and test-pitting. Washboring required pumping water from a wash tub, with a hand pump, and circulating the water through hand-operated drill rods. Wash water in the tub was replenished by carrying pails of water from a nearby stream. Great care was exercised in obtaining undisturbed tube samples. The Casagrande system of soil classification was used and every technician was thoroughly instructed in classifying the different soils. The first dam investigated was the Duncairn Dam in southern Saskatchewan.

The earlier dams were relatively small, but even there problems arose with seepage, slope protection and inadequate compaction. There were valuable lessons to be learned in preparation for the larger water control projects in the coming years. An example was the Wildhorse Dam in southern Alberta, where piping occurred near the base of the embankment due to inadequate compaction. Peterson used the Wildhorse Dam and other similar dams as case histories to determine the compaction requirements for the local soils in their particular environment. He then recommended practical procedures for achieving the necessary compaction. This was later documented in his paper entitled; "Study of Several Earth Dam Failures."[6]

In 1945, just before the large projects were approved for construction, Robert Peterson married Dorothy Stevenson. Although they came from neighboring farming areas they had not met until they studied in Saskatoon. They made their home in Saskatoon, Saskatchewan.

Iritus, an eye infection, as well as severe arthritis of the neck and upper spine plagued Peterson. This required occasional hospitalization and regular medication with cortisone.

Photo 2. View of Gardiner Dam and Lake Diefenbaker in central Saskatchewan.

Photo 3. Robert Peterson with visitors at the Gardiner Dam Opening, 1967
L to R: Dr. Spinks, President of U of S, Mrs. Spinks, Mrs. Peterson, Ms. Gardiner, Mr. Peterson.

Growth and Activities of the PFRA Soil Mechanics Division

The construction of numerous medium-sized dams and the planning of three major irrigation projects; the St. Mary and Bow River Projects in southern Alberta, and the South Saskatchewan Project, required a rapid increase in trained soil mechanics engineers and technicians.

The universities and technical schools were, as yet, not supplying people fully trained in this field. This necessitated a great deal of in-house training. Engineers were encouraged to take selected soil mechanics and geology classes at the university, and special training courses were set up for the technicians. Several percussion drills, a rotary diamond drill and a mechanized earth auger were added to the drilling equipment. More washbore units were formed and equipped with motorized pumps.

The laboratory space had to be enlarged to accommodate more sophisticated triaxial apparatus as well as concrete testing equipment. Studies were commenced on sulphate resistant cements and freeze-thaw durability of air-entrained concrete under the direction of Mr. George Price.

The division was responsible for all soil mechanics field investigations, laboratory testing, designs, field control testing, instrumentation and monitoring of all dams built by the PFRA. Field laboratories were also established at each major dam.

By 1951 the division had grown to more than 100 employees.

Peterson also recognized the value of contacts with outside soil mechanics specialists. Some of the early contacts were with soil mechanics staff at the University of Alberta and the soils researchers at the National Research Council of Canada. Dr. R.M.Hardy from the U of A became a frequent visitor and Mr. Lionel Peckover and Dr. Robert Legget were the regular contacts in Ottawa.

Participation in the National and International Soil Mechanics Societies and in their conferences was also an ideal way of exchanging and obtaining information. Later a close relationship was developed with the US Bureau of Reclamation and the US Army Corps of Engineers.

PFRA Projects

The first major dams, the Pothole and St. Mary Dams in southern Alberta, were to be 40 and 60 metres high respectively, and constructed mainly of a clay till. There was no precedent for this in Canada. Therefore a laboratory testing program was undertaken in which laboratory compaction tests were used to determine the maximum compacted density and the optimum water content for compaction. Direct shear and triaxial compressive strength tests were carried out on the compacted and in-situ samples. Consolidation and permeability tests were also performed on these samples. A test fill was then constructed to compare field compaction with the laboratory compaction. This then formed the basis for the specifications and field quality control. A field laboratory under Charles Ripley was set up and quality control tests were performed at regular intervals to ensure adherence to the specifications. This was a pioneering effort and provided a precedent for future dam construction. The installation of high-calibre instrumentation within the dam to monitor pore pressures and movements also was considered a first in Canada. Peterson's first paper in 1945[4] described the testing program and how these test results were used in the design. Theoretical studies were also carried out but the main emphasis was on field observations and past experience with other dams.

The St. Mary Dam was successfully completed and has functioned satisfactorily for 45 years.

The Travers Dam, a 45-metre-high earth-fill embankment in southern Alberta, was constructed on a Bearpaw shale foundation. At the time only limited information was available on this clay shale, and the term "residual strength" was not a fully appreciated soil mechanics term. The hope was that this dam would provide some valuable information on the performance of the clay shale foundation. Some slumping was evident in the abutments. Most of the disturbed material in the spillway area was removed but part of the spillway had to be constructed on a granular fillet in the unstable area. A comprehensive instrumentation program was undertaken. This included the relatively new tiltmeter (slope indicator), designed and built by Stanley Wilson. Embankment quality control was patterned after the St. Mary Dam specifications. No unusual movements or pore pressures developed during construction and this appeared to be a positive case history for future dams on clay shale.

Photo 4. Duncairn Dam in southern Saskatchewan. The first damsite investigated by Peterson.

The dam was successfully completed and has performed satisfactorily for over 40 years.

While the final location of the South Saskatchewan damsite was being identified major foundation problems became evident. A 30-metre-thick, relatively loose, alluvial sand deposit in the river channel posed serious seepage and settlement problems. Sampling techniques were developed for the retrieval of undisturbed sand samples. In-situ permeability tests using a central pumping well with radially spaced observation wells were performed, and standard penetration tests were carried out to assess the relative density of the deposit. Seepage studies and large scale model tests with steel sheet piling indicated that upstream blanketing was more effective than the sheet piling in reducing foundation seepage.

However, the main foundation problem was the Bearpaw Shale. There were too many unknowns in spite of the positive results observed at the Travers Dam. Slump topography dominated the river banks throughout the study area. Detailed geological studies were carried out by the PFRA's geologist, Dr. J. Mollard and others. Field slopes and landslide areas were analyzed to obtain an indication of the long-term field strength of the shale, and contacts were made with Imperial College in London, England where Dr. A.W. Skempton and others were working on the "Residual Strength Theory" to explain the long-term field strength of London Clays. Attempts at forcing the clay shale properties into the same mold were not entirely successful and Peterson realized that much more work was required.

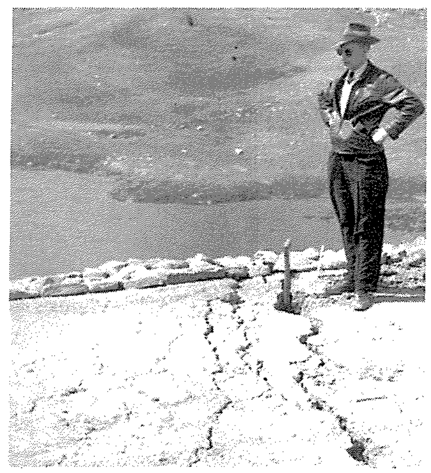

Photo 5. Peterson inspecting settlement cracks at Wildhorse Dam in southern Alberta.

The field and laboratory studies were intensified. Undisturbed samples were thoroughly inspected for geological defects, with special emphasis on bentonite layers and slickensided surfaces. Water content and Atterberg limit tests provided useful information in identifying these layers. Triaxial, unconfined and direct shear tests were carried out on undisturbed samples, slickensided pre-sheared samples as well as artificially sheared samples. Swelling pressures and magnitude of swell were measured in the laboratory and the field. Heave observations of a number of spillways on clay shale were already under way and more were added. Then two large-scale field tests were undertaken: a test tunnel in the soft shale of the river bank and an excavation site with hold-down piles. The test tunnel was instrumented to measure horizontal and vertical pressures on a tunnel lining, and the hold- down piles were monitored for heave, hold-down capacity and effectiveness.

Peterson recorded these studies in two more papers. The 1953 paper[5] was directed at the local construction industry and provided a general overview of the design and construction problems of PFRA dams, and the studies undertaken to resolve these problems. The 1954 paper[7] was prepared for the American Society of Civil Engineers and it described the Soil Mechanics and Geological investigations which had been undertaken to study the Bearpaw Shale. Initially these studies were carried out under the direction of C.F. Ripley, and later under A.S. Ringheim. The studies indicated that the shale could be divided into three zones; soft, medium and hard. Only the hard zone was considered to be a satisfactory foundation material. However, the origin of the highly slicked surfaces within the shale remained a matter of conjecture.

Besides the very heavy workload in the PFRA, Peterson also was requested to provide consulting advice on outside projects such as the unstable Seven Sisters dikes and other projects in Manitoba, the flood-damaged dikes on the Fraser River in B.C. and marshland rehabilitation in the Maritimes.

He usually managed to take a few days holidays in summer. The family's favorite resort was Banff. Here they went for leisurely walks in the mountains. Peterson particularly enjoyed a daily swim in the Upper Hot Springs Pool which helped to alleviate the arthritic discomfort in the neck and back. For ultimate relaxation he would then review and study soil mechanics papers which he hadn't had time to read during his busy work schedule.

Numerous other dams with special problems provided opportunities for additional studies. As the performance data accumulated, Peterson developed his own theory of dam design. It was based on experience, thorough field investigations, careful laboratory testing, good judgement and comprehensive instrumentation to monitor the performance of the structures during and after construction. In his 1957 paper[8] he discussed the major points in the design and construction of earth dams on the Prairies and highlighted important recent developments in earth dam engineering. The important effect of "minor geological defects" on dam safety had become a disconcerting problem.

The North Ridge Dam in Alberta was an important case history. A foundation failure occurred in the highly plastic clay when the embankment was nearly completed. A limited number of piezometers and movement gauges had been installed, but the warning signs given by the instrumentation had not been recognized. The follow-up investigation and analytical studies indicated

Photo 6. St. Mary Dam in southern Alberta. The first major PFRA dam.

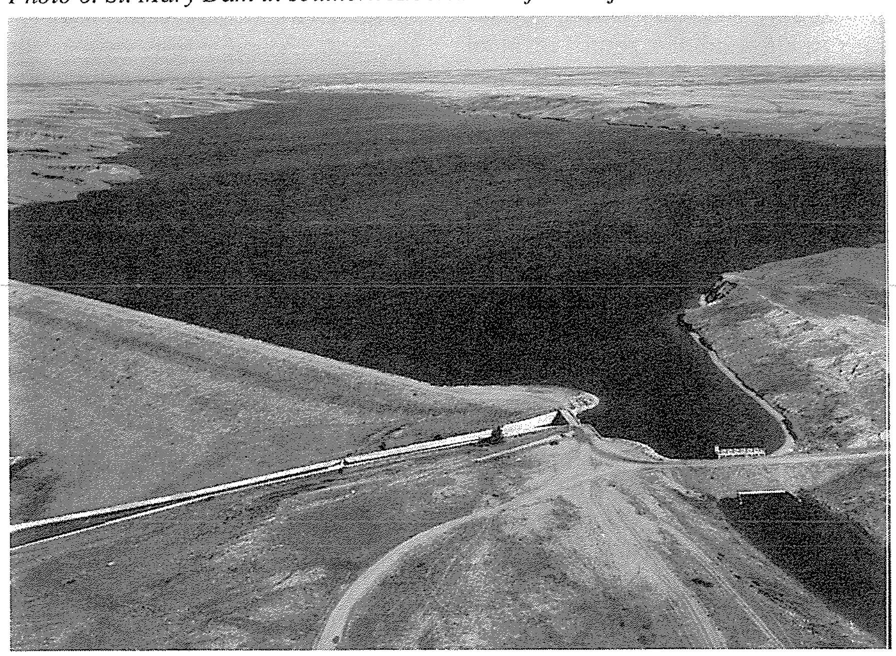

Photo 7. Travers Dam in southern Alberta constructed on Bearpay Shale.

Photo 8. The PFRA Soil Mechanics Building, later renamed the Robert Peterson Building, on the University of Saskatchewan Campus.

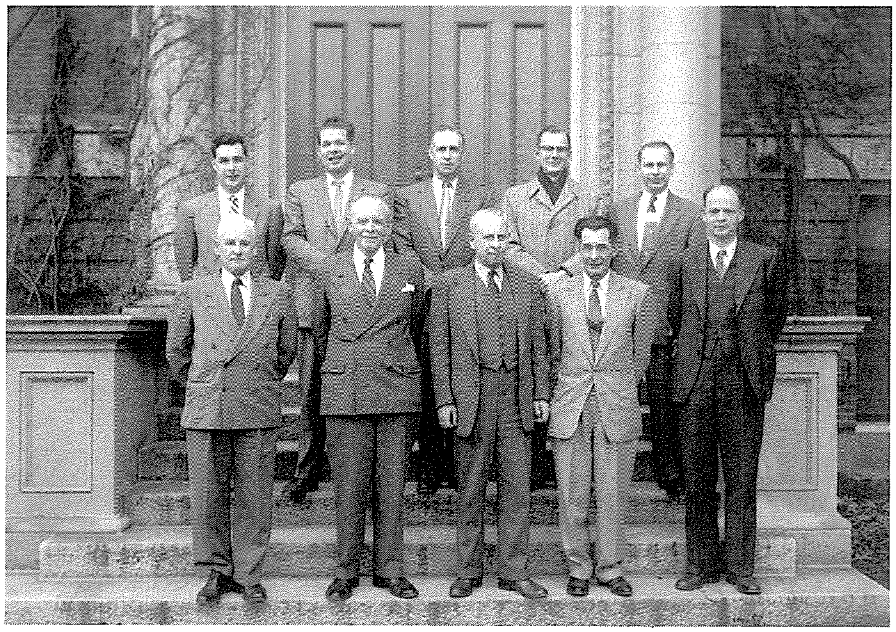

Photo 9. Meeting of PFRA engineers with the Consulting Board at Harvard University, 1954. Front row L to R:Mr. G. MacKenzie, PFRA Director, Dr. K. Terzaghi, Consultant, Mr. G. Munro, PFRA Chief Engineer, Mr. G. Parkinson, PFRA Chief Design Engineer, Dr. A. Casagrande, Consultant. Back row L to R:Mr. P. Rivard, PFRA Soil Mechanics Engineer, Dr. J. Mollard, PFRA Geologist, Mr. G. Watson, PFRA Project Engineer for Gardiner Dam, Mr. W. Johnson, US Army Corps of Engineers, Consultant, Mr. R. Peterson, PFRA Chief Soil Mechanics Engineer.

that the laboratory tests did not provide reliable information for design. Peterson et al documented this information in the 1957 paper[9] for the Fourth International Conference on Soil Mechanics and Foundation Engineering. They concluded, "Until such time as the stability of dams and foundations involving the more plastic clays can be predicted with greater reliability, observations of movements and pore pressures must be relied upon to warn of critical conditions."

Then in 1957 the go-ahead for Gardiner Dam was received. The office and laboratory facilities were already bursting at the seams, and, a new building with up-to-date testing equipment was placed on the order books. This was to include a large concrete testing laboratory with modern freeze-thaw apparatus. The building was located on the University of Saskatchewan Campus and was ready for occupancy in 1959.

An outside consulting and review board already was in place. It consisted of Karl Terzaghi, Arthur Casagrande, and Wendell Johnson of the United States Army Corps of Engineers.

At the same time, Peterson was also being called on to be a consultant for projects in and out of Canada. These included the Mangla Dam in Pakistan, the Panama Canal, and major power dams in Quebec, Manitoba, Alberta and British Columbia. He was active on committees and boards of engineering organizations such as: the Association of Professional Engineers of Saskatchewan, the Engineering Institute of Canada, the American Society of Civil Engineers, and the International Society for Soil Mechanics and Foundation Engineering. He contributed oral and written discussions at many national and international symposiums on soil mechanics and presented special lectures at Harvard, Berkeley and several Canadian universities.

A steady stream of correspondence issued from his office to engineers and researchers in the US Bureau of Reclamation, the US Army Corps of Engineers, to Drs. A.W. Skempton and D. Henkel in the London Imperial College, and to Dr. L. Bjerrum, Director of the Norwegian Geotechnical Institute.

The regular office hours did not suffice to complete all his scheduled work, so he took his work to his home basement office. His wife, Dorothy, typed all his consulting reports. For exercise and relaxation he spent short periods on his rowing machine or at his punching bag. Dorothy remembers that the thumping of the punching bag became more frequent as time went on.

Peterson updated his shale studies in two more papers. In 1958[10] he described the swelling properties and the rebound observations of the shale and concluded that the Bearpaw Shale was "probably the most expansive yet encountered." He also presented some practical procedures for dealing with the shale rebound when building on this type of foundation.

When the first edition of the *Canadian Geotechnical Journal* came into print in 1963 it included a paper by Peterson and Peters [11] entitled, "Heave of Spillway Structures in Clay Shales." Peterson later became a review editor for the Journal.

Construction of Gardiner Dam was

not a simple matter. Movements in the abutments and valley bottom became evident at the very outset. Pore pressures appeared to be erratic and tiltmeter measurements did not confirm surface movements. An improved piezometer seal had to be developed and tiltmeter pipe installations had to be extended well beyond the underlying "hard shale." To the consternation of everyone, the pore pressures quickly rose to nearly 100% of the embankment load, and a distinct movement zone was found 60 metres below the base of the dam in a soft bentonitic zone in the hard shale.

This required major revisions to the embankment cross section. Many more instruments, particularly tiltmeters were urgently needed.

A decision was made to proceed slowly , to carefully observe movements and pore pressures, and to revise the cross section, mainly flatten the slope, to ensure that the movement zone did not spread beyond the toe of the slope or even create an overthrust. This was the ultimate test of the "confirm-as-you-go design procedure" advocated by Peterson and the review consultants. Responsibility for the implementation of this program fell on the shoulders of PFRA Chief Engineer, J. Gordon Watson.

The downstream slope was eventually extended 700 metres beyond the original toe of the dam. Back-calculation of the shear strength of the soft layer showed that the angle of internal friction varied from 2 to 6 degrees and cohesion was equal to zero. This was unheard of. Even the initial rise of the reservoir triggered off a downstream movement of 0.2 metres.

The dam was safely completed under the capable leadership of the chief engineer and the conscientious efforts of the engineering staff at the construction site. The dam has been carefully monitored and the PFRA engineers and a board of consultants consisting of Ralph Peck, Stanley Wilson, Earle Klohn and Gordon Watson have regularly reviewed the observations. Gradually decreasing movements continued for 29 years as the reservoir refilled each year. In 1996 the movements became negligible.

In the meantime, the Shellmouth Dam in Manitoba presented the sum total of most of the soil mechanics problems experienced in all previous dams. The unstable abutments contained overconsolidated, highly plastic clay. The valley bottom consisted of 50 metres of alluvial deposits with thick soft clay layers interspersed with extensive pervious layers, and a massive highly pervious deposit at the base of the north abutment. The design, however, could now be based on a great deal of experience from earlier projects. This was done with a thorough drilling and testing program, comprehensive instrumentation, a test fill, careful assessment of all factors and a confirm-as-you-go construction policy.

Photo 10. Robert Peterson with PFRA officials and visiting geotechnical engineers at the Gardiner Dam control towers.

The dam was safely completed.

Geotechnical assistance was also given to the Canadian International Development Agency. A team of PFRA engineers and technicians under the direction of N.L. Iverson carried out field investigations for water resource projects in Ghana, Africa.

Throughout this busy period Peterson encouraged his engineering staff to participate in the activities of national and international soil mechanics organizations, the research and standards associations, and to co-author or publish independent papers.

Then in 1968 he published his last paper[12]: "Recent Trends in Earth Dam Engineering," in the EIC *Engineering Journal*. Here he summarized the experiences of his lifetime. In the section under Earth Dam Philosophy he stated: "Because of soil variations and our inability to establish satisfactory parameters, analytical studies cannot always be relied on.

In the solution of practical problems

the use of empirical methods and personal experience with similar situations is often more reliable—a confirm-as-you-go approach may be more appropriate than a design-as-you-go approach."

Peterson died of a massive stroke on February 9, 1969, at the age of 50 years and 10 months.

Contributions and Awards

Robert Peterson was a true professional engineer who was devoted to his work, to his fellow workers, and to public service. He was also a pioneer in the field of soil mechanics. He built up a capable and highly expert Soil Mechanics Division which carried out the geotechnical investigations and prepared designs for over 500 PFRA dams and projects, completed over 150 special research and design studies to resolve geotechnical problems related to earth dams, and published 34 papers.

In 1970 the Soil Mechanics Building on the University of Saskatchewan Campus was renamed the Robert Peterson Building. A plaque was mounted at the entrance stating: "In recognition of his outstanding contribution to Soil Mechanics and Civil Engineering Practice in Canada and abroad, and the warmth and integrity of his personal relationships, this plaque has been placed in memory of Robert Peterson by his colleagues in the Geotechnical Division of the Engineering Institute of Canada."

A few months later he, posthumously, became the first recipient of the Legget Award, for achievements of significance to Canada in the field of geotechnical engineering.

Notes

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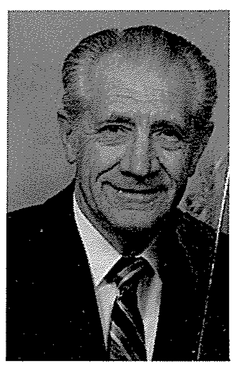

NICKOLAI (NICK) PETERS, on graduation from the University of Saskatchewan in 1949, was employed by the Prairie Farm Rehabilitation Administration, becoming chief of the Geotechnical Division 1975-84.

The PFRA work involved the investigation, research, design, construction control, and monitoring of dams and appurtenant structures including, in Alberta, St. Mary, Pothole and Waterton dams on the St. Mary Irrigation Project, the Travers, Carlsland and McGregor dams on the Bow River Irrigation Project, the Shellmouth Dam in Manitoba, and the Boundary, Qu'Appelle and Gardiner dams in Saskatchewan.

Peters also took on special assignments as geotechnical consultant for the Canadian International Development Agency mission on water resource studies in Tanzania and the design review of the Feni Dam in Bangladesh. From 1985-94 he was a private consultant in the performance and safety evaluation of dams in Saskatchewan

Mr. Peters has authored papers on earth dam performance and evaluation. He received the Canadian Geotechnical Society Award in 1980 as co-author of the paper, "Foundation Performance of Gardiner Dam."

Robert Ferguson Legget and the National Research Council of Canada

Carl B.Crawford

The first purpose of this paper is to give a glimpse of the personality of Robert Legget for the benefit of younger members of our profession who did not know him or who saw him only when he presented the prestigious Legget Award at the Annual Canadian Geotechnical Conferences. In an attempt to reduce my own biases I have quoted others whenever appropriate.

Robert Legget was born in Liverpool on September 29, 1904. He died in Ottawa on April 17, 1994. A graduate of the University of Liverpool (England) in 1925 with a B.Eng. in Civil Engineering and an M.Eng. in 1927, he immediately joined a firm of consulting engineers carrying out design and construction work for the Lochaber power project in Scotland. He came to Canada in 1929 to work with the Construction Division of the Power Corporation of Canada, and later as a design and construction engineer with the Canadian Steel Sheet Piling Company of Montreal.

Legget was by nature a gentleman in word and deed—some would say a Victorian gentleman. He had many friends around the world and kept in touch regularly by mail and telephone. The extent of his correspondence, even in his busiest years, was phenomenal. He traveled widely and used every minute for personal or official communication, always leaving the train or aeroplane at stops to mail postcards or to telephone local friends and acquaintances.

My first encounter with him was when Dean Douglas Ellis ushered a handsome, youthful looking man with jet black hair into a classroom at Queen's University during the fall term of 1948. Ellis introduced us to Professor Robert Legget who was still commuting between the University of Toronto and the National Research Council where he was establishing the Division of Building Research. That evening Professor Legget spoke to the Queen's Engineering Society about his plans for the new division. Even in those bountiful days when there were five jobs available for every graduate, I was captivated by the man and decided I wanted to be part of his exciting new activity.

Robert F. Legget.

I already knew of his work through his book *Geology and Engineering*, which was used as a reference in our introduction to the importance of geology in civil engineering practice, and this stimulated my career interest in soil mechanics. Like many of my colleagues at NRC he became my mentor and cherished friend for 45 years.

The Author

At an early age Robert Legget began keeping notes on his activities and forming them into interesting accounts for publication. When he came to Canada he continued the practice of writing up his construction experiences for the engineering literature, and in 1932 he responded with enthusiasm to a request from *Engineering News-Record* for an article on the construction of the Upper Notch power plant, located on the Montreal River in northern Ontario, where he was serving as resident engineer. The contribution must have made a favorable impression because in 1933 *ENR* invited him to be their engineering correspondent in Montreal, a position he expanded (in his spare time) into being their Canadian correspondent for the next 50 years.

These early construction experiences persuaded him of the value of geology in civil engineering works, especially the geology of soils. He discussed his views with Dr. J.J. O'Neill, the distinguished professor of geology at McGill University, who agreed completely with his assessment. O'Neill suggested he should write a paper on the subject because, he said, "If you really want to learn something, the best way is to try to write about it," (advice often passed on by RFL to his younger colleagues). The paper was published in the *Journal* of the Engineering Institute of Canada in 1934. In 1939, his first major book *Geology and Engineering* was published. A third edition appeared in 1983. Along the way there were another dozen major books and four others where he acted as stimulator and editor.

The Speaker

In the February/March 1982 issue of *Canadian Geographic*, author Betty Baird wrote: "No one at the banquet coughed or fidgeted. All attention was riveted on a short, stocky man who was talking about a canal in the Canadian wilderness and about the man who built it. The speaker enthralled his audience of scientists and mining professionals with his vivid imagery, impeccable diction and the resonance of his voice.

"Robert Legget—candid and courtlyis a superb speaker and, if his subject is close to his heart, his words seem to acquire a magical flow. On this particular occasion he told the story of Lt. Col. John By, the British military engineer who in 1826 was sent into rough, mosquito-infested bush country to build the Rideau Canal as an alternate water route from Montreal to Lake Ontario for use in the event of war with the United States.

"Robert Ferguson Legget, is a modest man, self-effacing about his own abilities but generous in applauding others. The wonderful people he worked with, or the inspiration of people who taught me, or the great good luck that happened to come his waythese, he insists, are the things that shaped his destiny, and his successes in life.

"Yet this Canadian by adoption is a distinguished engineer, geologist, author and historian. An inveterate traveller who knows the face of Canada intimately, he is also something of a geographical impresario. His discovery of history put a new sheen on old canals and locks and waterways; and his writing and speaking on all of these things has kindled in his readers and audiences a more deeply felt appreciation of this land he chose."

In the multitude of popular talks he gave on the subject, Legget was always passionate in his admiration of Lt. Colonel By, founder of Bytown, now Ottawa. These talks were based on an exhaustive research of By and his work which Legget documented in his book *Rideau Waterway*, published in 1955, with a second edition in 1986. He was delighted to be asked to tell "The Rideau Canal Story" for a video production made shortly before his death.

His popularity as a speaker brought numerous requests for special lectures, memorial lectures and convocation addresses. Even in his 90th year he received many more requests than he could satisfy. He began his own training by participating in debating clubs at school and university and passed useful tips on speaking to his staff at the National Research Council, where he initiated weekly technical seminars to help researchers develop their speaking skills and get critical reviews of their work.

The Teacher

"Robert Legget must have been an inspiring teacher at university 50 years ago because he still is today at age 90. He's also one of Ottawa's greatest treasures" wrote Peter Calamai in the *Ottawa Citizen* after a two-hour interview for a piece on the Rideau Canal.

During his 11 years in engineering practice he became convinced of the need for research and education related to soil and geology. In 1936 he made a deliberate career change to teaching, first at Queen's University, and then at the University of Toronto. His students remember him as a superb teacher, his eloquently delivered lectures were always well prepared, and sprinkled with practical examples from his own experiences or from published case histories. When I was invited to give a course on Soil Mechanics at Carleton University he loaned me his lecture notes from the University of Toronto. Although they were somewhat out of date, it was interesting to observe the care with which they were prepared. Each lecture, handwritten in a bound notebook and dated, had marginal notes recording items that appeared to give difficulty to the students, so they could be rewritten for the next year. After World War II there were many senior engineers who had come to appreciate the value of soil mechanics in their wartime construction but had not had any training in the subject. Legget was urged by several prominent engineers to develop a practical short course to satisfy the expected demand. He organized a one-week course through the university Extension Department and within 24 hours of its announcement it was filled to capacity with 150 mature students.

The Consultant

Professor Legget's first major consulting job after joining the University of Toronto came in 1938, through his department head, Dr. C.R. Young. Dr. H.G Acres asked him to do the soil testing and provide advice on the construction of an earth dam, the Shand Dam on the Grand River near Fergus, Ontario. Legget was just setting up his laboratory but in those days soil properties were determined by visual inspection and simple tests for grain size, permeability, soil compaction and direct shear—a far cry from modern testing and analyses.

During World War II all engineering professors were encouraged to stay at their posts to continue the education and training of new students, and in his spare time Legget became involved in consulting on some major wartime projects, such as the Shipshaw Power Project to supply the aluminum smelters at Arvida in Quebec, the Polymer synthetic rubber plant at Sarnia, Ontario to replace the natural rubber sources cut off by the war, and the development of the Steep Rock Iron Mine at Atikoken in northern Ontario to secure iron supplies for war production. He also spent a summer in the North assisting with the organization of the Mackenzie River Transport Company without knowing it was being prepared for the shipment of uranium to the south. This assignment developed into a lifetime interest in the challenges of building in the North. When he came to the NRC he passed the challenge to a small staff that studied the character and occurrence of permafrost and the performance of structures founded on permafrost; studies that led to the production of the Permafrost Map of Canada and many papers dealing with design and construction in the North.

In 1944 Professor Legget was invited to assist the Toronto Transportation Commission on subsurface studies for a proposed subway. He first consulted the Ontario Department of Mines and several of the interested consulting firms to find out what subsurface information was available. As a result he was able to piece together a pattern of the geology, which was confirmed by test borings along the proposed route. This information was made available for tendering and for contract drawings (unusual at the time) with the result that bids were very close and there were no major claims at the end of construction.

When he joined the NRC Legget gave up all consulting work, but he applied his leadership talents to the encouragement of his young staff in developing a wide range of technical expertise for the construction industry.

The Division of Building Research

A book titled, *The Mackenzie-McNaughton Wartime Letters* describes the important influence of these two distinguished Canadian engineers on the spectacular advance in Canada's science and engineering during World War II. In an epilogue to the book Dr. Mackenzie wrote:

"The Building Research Division, founded in 1947, was set up to fill a gap in a mission-oriented field where applied scientific research was an urgent national need. This division was planned with wisdom and built up with unusual dispatch by its first director, R.F. Legget. It was designed to function primarily as a cooperative scientific aid to the civil engineering problems of the building industry in general, and as a research establishment in particular for the vital and comprehensive field of housing in all its varied aspects. Its laboratories were focused on urgent scientific studies in a field where, for much too long, outmoded empirical rules and procedures governed specifications and construction. Non-laboratory studies brought a National Building Code that introduced scientific rationality into a field where individual codes had often been based on local prejudice and customs of yesteryear. Sections on standards for building materials were set up to reduce real costs. Architectural concern with design problems, such as space utilization, acoustics, and insulation, came to be studied jointly by interdisciplinary groups which did not consider factors of structural safety and economics incompatible with aesthetic values and reasonable amenities of living, so important to the comfort of a home owner. The division soon became an informal but very real scientific adviser to both the Department of Public Works and the Central Mortgage and Housing Corporation. In addition, committees of practising architects, builders, and experts from every field, interested in the details of planning and administration, became consultants and advisers to the division. In this way, the division achieved the unique result of bringing its contributions in applied science into direct contact with hundreds of professional designers and builders and thousands of individual consumers."

The invitation from Dr. Mackenzie, President of the National Research Council of Canada, presented Legget with the challenge of providing a research and information service for the Canadian construction industry. From the beginning he emphasized that DBR, as it became widely known, was to be a source of information based on the world literature, supplemented by field and laboratory work on problems that were of special interest to Canada. Consequently he organized research on a complete spectrum of building problems, with emphasis on those arising from building in a cold climate and on a varied terrain.

Legget took up his assignment in August 1947 and by 1949 he had a staff of twenty and a clear idea of what was needed. During the year the staff was doubled to about forty and it was spread around the Montreal Road site of the NRC at Ottawa. By then there was a demonstrated need for new facilities, so planning was begun for a Building Research Centre. During the design and construction for this new building Legget maintained a close personal interest in all aspects of the project. It was, he said, the first building ever erected to serve the general needs of building research. The Division, now with a staff of 90, moved into its quarters in June 1953. In October 1953 he organized the first Conference on Building Research to be held in Canada, and during the conference the Building Research Centre was formally opened by the Right Honourable C.D. Howe, then Chairman of the Privy Council Committee on Scientific and Industrial Research.

These were exciting times. Canada was in the midst of a construction boom catching up on the post-war needs for housing, commercial space and facilities for transportation and urban developments. Dr. Mackenzie identified two special needs for the new Division in addition to its general research program. These were the need to revise the original National Building Code (published in 1941) and to provide technical support to the newly established national housing agency, Central Mortgage and Housing Corporation. Both of these programmes were strongly supported.

In 1947 there were more than 4,000 municipalities in Canada that were nominally responsible for building regulations. Only a few of the larger towns and cities had building codes and many had no regulations at all. Legget and his staff began to assemble a national list of individuals who had responsibility for building regulations, and so began the communication that is so essential to cooperation. The Associate Committee on the National Building Code was established under his chairmanship with members drawn primarily from experts in the private sector and as appropriate from academia and governments. DBR was organized to provide technical support and other assistance. By the time he retired in 1969 the National Building Code, which is revised every five years, was in use across the nation, a remarkable achievement in this large and diverse country. The Code also provided the technical basis for CMHC housing regulations. Similar support was given to the later development of the National Fire Code.

He set a broad agenda for the ACGR, including the study of permafrost, muskeg, and soil, snow and ice mechanics. . .

His early background in design and construction and his experience in teaching and consulting convinced Legget that it was essential "to develop building research in Canada in the closest possible liaison with construction operations as well as with design professionals." In following this principle he encouraged his staff to take an active part in professional and technical societies and to prepare publications that could be easily understood and applied by busy practitioners. For his success in these endeavors he was honoured as the the first recipient of the Gold Medal of the Canadian Council of Professional Engineers, an Honourary Fellowship in the Royal Architectural Institute of Canada, and Life Membership in the Canadian Construction Association. In a single year in the 1960 s he was president of the American Society for Testing and Materials, the Geological Society of America, and the Conseil Internationale du Batiment. All of these major responsibilities were carried on while fulfilling his primary duty as Director of the Division of Building Research. In 1987 he was the Founding President of the Canadian Academy of Engineering.

In the early days of the Division Dr. Legget recruited many young members to his staff, but he also managed to find a few people with research experience. Fortunately, in 1952 he was able to convince Dr. Neil Hutcheon, then at the University of Saskatchewan, to join DBR as his assistant (and later successor). Together they formed a powerful team. Hutcheon brought a keen, analytical mind and a fundamental appreciation of building science to the Division, as well as a few of his outstanding graduate students. This proved to be an enormous benefit to the development of new and unique facilities and to the education of many young members of staff.

The Associate Committee on Geotechnical Research

Legget's greatest opportunity to influence the development of geotechnique in Canada was through the Associate Committee on Soil and Snow Mechanics, later named the Associate Committee on Geotechnical Research (ACGR). The Committee, established by Dr. C.J. Mackenzie, held its first meeting on April 20, 1945, with Legget as Chairman, to monitor some wartime research on tracked vehicles. Later it developed its peacetime purpose, "to co-ordinate and stimulate research on the engineering and physical aspects of the terrain in Canada." He set a broad agenda for the ACGR, including the study of permafrost, muskeg, and soil, snow and ice mechanics, always with the participation of geologists and pedologists and with a determination to unite research and engineering practice across the country. Through the Associate Committee he invited all known workers in soil mechanics in Canada to a two-day meeting in Ottawa. This first Canadian Soil Mechanics Conference was held on April 28-29, 1947, with 40 people in attendance. Most of the first meeting was devoted to reports from regional representatives describing activities in their areas. Regional representatives were made members of a Subcommittee on Soil Mechanics and this was the birth of the local groups that have been so important to communication in this large country.

Only a few will remember that the first individual grants for geotechnical research at universities were made in 1947 from the budget of the Associate Committee. Requests from academics for funding of geotechnical research grew very slowly, in spite of the Associate Committee's urging, but in 1959 the requests exceeded the Committee budget ($20,000) for the first time, while the total NRC support to universities was about $6 million. Legget was delighted with the developing interest in geotechnical research and he approached Dr. E.W.R. Steacie, then President of NRC, for more money. It was then that Dr. Steacie set up a special Office for University Grants which began providing increasing funds for engineering research. The office later became the Natural Sciences and Engineering Research Council.

The impetus for the establishment of the *Canadian Geotechnical Journal* began with the Toronto Geotechnical Group in 1961. The idea was considered at a joint meeting of the ACGR and the Geotechnical Engineering Division of the Engineering Institute of Canada. But financial and legal restraints (primarily in the EIC) inhibited action. Finally Legget solicited personal financial guarantees from 20 individuals to secure the financing of the first two issues and the Journal was launched in 1963 with Victor Milligan as editor. Although the NRC was publishing the *Canadian Journals of Research* in support of the sciences, it was reluctant to provide similar support for engineering, in the belief that there was not sufficient need. Finally they agreed to make cash grants to the Journal in 1967 and 1968, and after much discussion and pressure from the ACGR, they adopted the Journal as one of their own, beginning in 1969.

Robert Legget was the last survivor of the eight Canadians registered for the First International Conference on Soil Mechanics and Foundation Engineering held at Harvard University, June 22-26, 1936, where he met Terzaghi and other engineering leaders from Canada, the USA and other countries. Recently he described the meeting as the most pleasant and rewarding he had ever attended. Typically a full account of the meeting by Legget appeared in the August 1936 issue of *The Engineering Journal*. Similar overview accounts of all of the conferences of the society that he attended have appeared.

"In my six decades here, I have grown to love this country and land. And I find it passing strange to be receiving this Award. . ."

One of Dr. Legget's great satisfactions was, while Vice President for North America, to persuade the ISSMFE to hold it's sixth International Conference in Canada. He was chairman of the organizing committee, and under his watchful eye, the conference was staged in Montreal in September 1965. It resulted in an excellent set of proceedings which eventually produced a profit of more than $30,000. The NRC had underwritten much of the cost and therefore demanded the profit. However, the private sector had also contributed funds and Legget argued that those funds would also have to be returned. After much discussion the VP of NRC finally agreed to leave the money with the ACGR for the support of geotechnical research in Canada. This became the Canadian Geotechnical Fund for support of the Cross-Canada Lecture Tours and other important activities.

Robert Legget's greatest contribution to the Canadian geotechnical community was his foresight and sound organizational ability which drew together interdisciplinary workers from coast to coast in what evolved into the Canadian Geotechnical Society, considered by many the most successful engineering society in Canada. When he retired from the NRC in 1969 the Canadian Geotechnical Society established the R.F. Legget Award in his honour.

Accolades

Few people are able to make as great an impact on their profession as Robert Legget. He was an exemplary leader who subscribed to a rigid code of ethics and a devotion to public service. His ability to create an environment that enabled others to contribute is as significant as his personal contributions. When he retired from the NRC in 1969 he revived his contributions to engineering geology and renewed his interest in engineering history, producing many journal articles and several books on these subjects.

Writing was obviously a form of recreation for him for even in his busiest periods he continued to contribute articles and comments on a wide variety of subjects beyond his immediate fields of interest. Fortunately his papers have been sorted, catalogued and stored in the National Archives of Canada where they occupy 20 volumes containing a total of 653 files. It is a fascinating trail for those who follow.

In recognition of his contributions, Robert Legget has been widely acclaimed with twelve honourary degrees and fifteen special awards from professional and learned societies. In 1980 his original professional society, the Institution of Civil Engineers in London, awarded him Honourary Fellowship, an honour limited to twenty persons. He was especially proud to be appointed an Officer in the Order of Canada (O.C.) in 1967 and elevated to a Companion in the Order (C.C.) in 1989. All of these honours were accepted with humble dignity and always with tributes to those who helped. To know him was to know compassion and true public service with probity.

When he accepted the Royal Bank Award in 1989 our distinguished friend and colleague said: "In my six decades here, I have grown to love this country and land. And I find it passing strange to be receiving this Award for what I am said to have given to it when I know that I have received far more from Canada than I have ever given in return." On this score we disagree and I am sure that there are many, many Canadians who are extremely pleased and grateful that in 1995 the National Research Council chose to perpetuate the memory of this remarkable man by naming the Building Research Centre the R.F. Legget Building.

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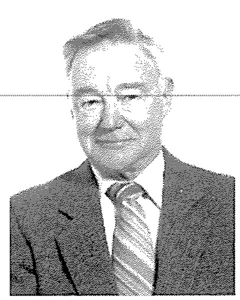


CARL B. CRAWFORD was born in Dauphin, Manitoba. After serving in the RCAF during World War II, he received his civil engineering degree from Queen's University, Kingston in 1949. He took graduate training in soil mechanincs at Northwestern University and the Imperial College of Science and Technology, London, England. In 1984 he was awarded an honourary L.L.D. from Concordia University, Montreal.

Crawford joined the Soil Mechanics Section, Division of Building Research, National Research Council of Canada in 1949 as a research officer, became head of the section in 1953, assistant director NRC/DBR in 1969, and director in 1974-85.

Crawford has a long record of service to many technical and professional organizations. He has contributed greatly to soil mechanics research in Canada, has authored many research papers, and is the recipient of several honours and awards. He is currently adjunct professor at the Memorial University of Newfoundland and the University of British Columbia.

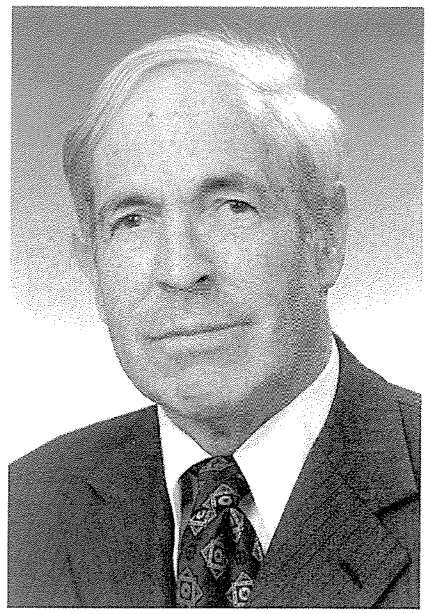
George Geoffrey Meyerhof

Leslie D. Baikie

George Geoffrey Meyerhof is well known to geotechnical engineers in Canada and abroad. Over the past fifty years his involvement in soil mechanics research, education and consulting has contributed to the advancement of our knowledge of the principles and practice of geotechnical engineering. To engineers in the field of foundation engineering he is probably best known for his publications dealing with the bearing capacity of shallow and deep foundations and the correlations that he developed between field tests, especially the standard penetration and cone penetration tests, and the bearing capacity and settlement of foundations. These early contributions continue to be in everyday use in geotechnical engineering design and construction.

Family and Education

George Geoffrey Meyerhof was born on 29 May 1916, in Kiel, Germany, the oldest of three children of Professor Otto F. Meyerhof, M.D., and Hedwig Schallenberg. Geoff's father was a professor at the University of Kiel where his work on cellular oxidation led to the discovery of the formation of lactic acid in muscles for which he shared the 1922 Nobel Prize, with Professor A.V. Hill of Manchester University, for Physiology or Medicine. In 1924 the family moved to Berlin where Otto Meyerhof joined the Kaiser Wilhelm Institute for Biology, and in 1929 he became Director of the Kaiser Wilhelm Institute for Medical Research at Heidelberg. Geoff graduated from the Gymnasium in Heidelberg in 1934 and emigrated to Great Britain. His parents remained in Heidelberg until 1938 when, for political reasons, they too left Germany and after spending three years in France, moved to Philadelphia in the United States where his father became Research Professor of Biology at the University of Pennsylvania. Otto Meyerhof passed away in 1951. The research that earned for him the Nobel Prize in 1922 remains a basic contribution to the understanding of biochemistry and has become known as the Pasteur-Meyerhof reaction.



G.G.Meyerhof.

In 1935, after having left Germany, Geoff entered University College at the University of London, and graduated in 1938 with a B.Sc. degree and with the Diploma in Civil and Municipal Engineering. His first introduction to soil mechanics came in 1938 when he began postgraduate studies for a M.Sc. degree at University College under Professor P.L. Capper. In 1939 at the Institution of Civil Engineers in London he attended a lecture by Karl Terzaghi on "Soil mechanics: a new chapter in engineering science," and subsequently a series of lectures at ICE by Len Cooling, Alec Skempton, Hugh Golder and others on "The Principles and Application of Soil Mechanics."

Geoff says, "As a result of the interest that these lectures generated in me, I thought I'd look at the subject a little more closely, on the basis of home study, because it was not available at the University at that time."

He studied *Erdbaumechanik* by Terzaghi, as a basic introduction to the subject, *Earth Pressures and Bearing Capacity of Soils* by Krey, for statics of soils and bearing capacity of foundations, and *Subgrade and Structures* by Kogler & Scheidig, for soil-structure interaction.

He undertook post graduate research as an external student at the University of London. In 1944 he was awarded the Master of Science (Engineering) degree for his thesis on "The Bearing Capacity and Consolidation of Soils and Settlement of Foundations," which was a digest of the then existing knowledge on the bearing capacity of soils and the settlement of foundations. His later research dealing with the bearing capacity of foundations, which he began in 1946, earned him the Ph.D. degree in 1950.

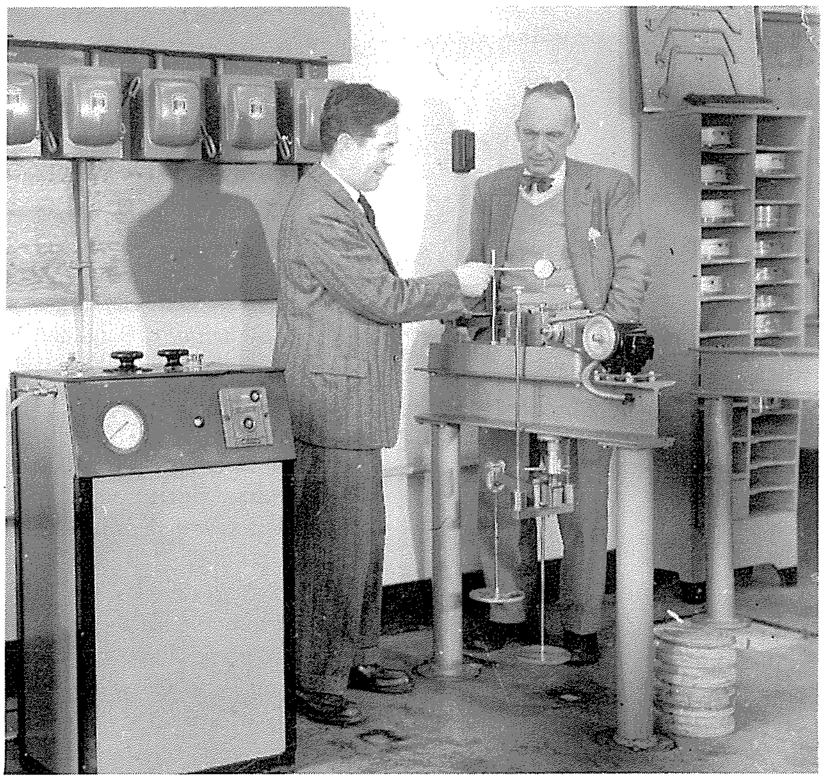
On February 22, 1947, Geoff married Elisabeth and in 1948 their first of two sons, Thomas Paul, was born. Their second son Peter George was born in 1951. His wife Elisabeth died in early 1984, and Geoff remarried in December 1984 to Ingrid (Susi) Goering.

Engineering Experience and Early Consulting

On graduating from university in 1938 Geoff began his engineering career with Arup & Arup, London. Then, in 1939, during World War II, he became an engineer and designer with Expanded Metal Company, London, responsible for the designs and estimates for buildings, bridges, industrial structures and public works and the inspection of materials and methods of construction. In 1943 he became Principal Designer to the Expanded Metal Company and Structural and Soil Mechanics Engineer to R.H.H. Stanger, London (Testing Works). With R.H.H. Stanger he was engaged in the inspection and testing of building materials and structural components and was in charge of their soil mechanics department. He carried out site surveys, soil explorations and tests for airports, dams, earthworks, earth retaining structures and foundations of all types in connection with the war.

At the Expanded Metal Company he did some experimental work on fabricated steel girders, reinforced concrete beams and slabs and reinforced brickwork construction. After completing a series of performance tests on steel members, he assisted in the draft of the British Standard Specification for "Expanded Metal" and for "Concrete Reinforcement."

In 1946 Geoff was invited to join the staff of the Building Research Station of the Department of Scientific and Industrial Research (DSIR) at Garston near London, which had the oldest British geotechnical research department under Len Cooling. Other colleagues at BRS were Alec Skempton and Bill Ward. Later the same year during a visit to BRS by Karl Terzaghi, he was asked by Terzaghi: "Meyerhof, why don't you investigate the bearing capacity of foundations?" A research team was formed with Theodore Chaplin and two technicians and, as part of the research program, model tests were made on footings and piles in sand, clay and rock, to study the bearing capacity of foundations. The results of some of this research were incorporated in his Ph.D.thesis on "Bearing Capacity of Sand," in 1950 at the University of London. His research also resulted in a number of publications for which he was awarded a D.Sc.(Eng.) degree by the University of London in 1954 for "distinct contributions to structures and foundations."



G.G. Meyerhof and Client, Soil Testing Laboratory, NSTC, Halifax. 1956.

In 1946 BRS was visited by Robert Legget prior to his appointment as first director of DBR/NRC of Ottawa, and by Bob Hardy of the University of Alberta, Edmonton. In 1947 Geoff participated with Len Cooling on a government mission to Canada and the USA to renew contacts with public research organizations and universities for exchange of information on recent soil mechanics research. They visited Canadian laboratories at the University of Toronto (R.F. Legget), the University of Montreal (J. Hurtubise), PFRA (R. Peterson) and others. During this visit Geoff participated in the 1st Canadian Soil Mechanics Conference at Ottawa, summarizing British soil mechanics research (representing Cooling who was ill with an infection). In the USA they visited Harvard (Casagrande, Arthur and Leo), MIT (Don Taylor), Princeton (G. Tschebotarioff), Columbia Univ. (D. Burmister), Univ. of Illinois (R.B. Peck), Yale (D. Krynine), Univ. of Washington (R.G. Hennes) and some government research laboratories.

At the Building Research Station, Geoff was a Scientific Officer in the Soil Mechanics Division and engaged in research on various soil and foundation problems. In 1947 he was promoted to Senior Scientific Officer and subsequently to Principal Scientific Officer, and became Head of the Foundation Section of the Soil Mechanics Division where he was in charge of soil investigations for large public buildings, bridge and industrial structures. He carried out estimates for the stability and movements of foundations, field tests and observations on their behaviour, investigated foundation failures and designed remedial measures for various types of structures. He assisted in the draft of the first British Standard Codes of Practice for "Foundations" and for "Earth Retaining Structures."

In 1947 he became a member of the Foundation Research Committee of the Institution of Structural Engineers where, among other work, he assisted in the draft of the Technical Report on "Mining Subsidence and its Effect on Structures." During this period he frequently lectured and read papers on structural engineering and soil mechanics subjects at educational and professional centres. He also acted as expert witness in High Court. As well he undertook theoretical and experimental work on the strength and deformation properties of soils, the indentation and penetration of various materials, the bearing capacity and settlement of foundations and the effect of foundation movements on the behaviour of structures. He was engaged on laboratory and field research on behaviour of shallow and deep foundations of buildings, bridges (Deptford Creek), and industrial buildings in Greater London; soil-structure interaction (Whitehall Gardens), foundation failures and design of remedial measures for a factory building on fill, a large water tank on soft clay of variable thickness, and single-storey portal frame buildings. The Deptford Creek Bridge project in London is vividly remembered by Geoff, "... the bridge had been damaged by bombing during the war and had to be rebuilt, and since I was working on foundations, I was very keen to do some field tests, and we did tests on different sizes of plates at the bottom of a large test caisson. In order to get the water level up to the level of the base, because the foundation itself would be in water, I shouted up to the foreman to reduce the air pressure a bit! Since the base may be about 20m below the level of the Thames, and one cannot adjust the water level so accurately, suddenly the sand bottom on which Chaplin and I were standing, became quick, we left all the equipment in place and hung on to the ladder. We saw the air steam up with this reduction in air pressure and shouted to put the air pressure back again. This was done, the air cleared and we gratefully left the caisson, climbing up the 20m on the ladder to get to the airlock and out again. I must admit, for a number of months I did not tell my wife, Elisabeth, about the terror I escaped; nor did Chaplin tell his wife!"

In the fall of 1953, following discussions with R.F. Legget, he emigrated with his family to Canada to join the Foundation Company and FENCO in Montreal where he became further acquainted with Bob Shaw, Per Hall, Norm Lea and others of FENCO, Jacques Hurtubise of Ecole Polytechnique, Bob Hardy of the University of Alberta, Leo Fraikin of Franki Canada, Bob Petersen of PFRA, Chris Fisher of ARMCO and others who had done pioneer work in geotechnical engineering in Canada for many years. At the Foundation of Canada Engineering Corporation, Montreal, Canada, he was appointed Supervising Engineer in charge of the design of Highway Bridges for the Trans-Canada Highway (Cataraqui River Bridge, Little Pic Bridge and Steele River Bridge); the foundations for the Burlington Skyway Bridge, Ontario; the stability of the Deas Island Tunnel and the stability of the Nanaimo Ferry Terminal, B.C.

Teaching and Research

Geoff joined the Nova Scotia Technical College (later the Technical University of Nova Scotia) in 1955 as Professor of Civil Engineering and Head of the Department of Civil Engineering. He lectured at the undergraduate level in the subjects of soil mechanics and foundations, history of engineering, and at the graduate level: advanced soil mechanics and earth structures; and advanced foundation engineering; advanced theoretical soil mechanics. He set up undergraduate laboratories for soils, foundations, construction materials, and for advanced soils research. He took on additional duties as Director of the School of Graduate Studies from 1962-1964, and as Dean of the Faculty of Engineering from 1964-1970.

In addition to undergraduate and graduate courses at NSTC he taught extension courses on soil mechanics to professional architects and engineers, was guest lecturer at various universities in Europe, North and South America, Israel, Japan, and China, and he gave numerous papers. He was general reporter at several national and international geotechnical conferences, such as Session I on "Soil Properties and their Measurement," 5th ICSMFE, Paris 1961; the Session on "Piled Foundations," 2nd Pan Am. Conf. SMFE, Sao Paulo 1963; the Session on "Theories," ASTM Symposium on Laboratory Shear Testing, Ottawa 1963. During 1964/65 he was on the Organizing Committee for the 6th ICSMFE, Montreal, under the chairmanship of Robert Legget. He represented Canada at several international conferences and special events, such as the Vice-Chairman, Main Session I, 8th ICSMFE, Moscow, USSR, in 1973; General Reporter for "Countries outside Europe," ESOPT, Stockholm, Sweden in 1974; the 5th PanAm Conf. SMFE, Buenos Aires, Argentina, in 1975; the 6th ECSMFE, Vienna, Austria, in 1976; the ICE Reception of Queen Elizabeth II for her Silver Jubilee, London, UK, in 1978 as the ICE Council Member for Canada; the 7th ECSMFE, Brighton, UK, in 1979; and the 6th PanAm Conf. SMFE, Lima, Peru, in 1979; Co-Chairman Session 8, "Pile Foundations," 10th ICSMFE, Stockholm, Sweden, in 1981; Closing Address, Int. Conf. on "Advances in Piling and Ground Treatment for Foundations," ICE, London, U.K., in 1983; Keynote Lecture, 1st Int. Geotech. "Seminar on Deep Foundations on Bored and Auger Piles," Ghent, Belgium, in 1988; Keynote Address, Int. Symp. on "Limit State Design in Geotechnical Engineering," Danish Geotechnical Society, Copenhagen, Denmark, in 1993.

Geotechnical research at the Technical University of Nova Scotia (Nova Scotia Technical College) involved 35 M.Eng. students, 7 Ph.D. students, as well as 12 Post Doctoral Fellows and several research assistants and research associates with financial support from government, industry, and university administration. Initially graduate laboratory research was carried out on skin friction between soils and various construction materials in relation to retaining walls and foundation problems. Later, most of his research problems concerned the bearing capacity and settlement of vertical and batter model piles, and with pile groups under eccentric and inclined loads in sand and clay, a subject which became important in connection with offshore structures. Subsequently, the bearing capacity and settlement of shallow and deep foundations in layered soils were studied to represent soil conditions in practice, and the problem of accident risk and safety factors.

Most of the field research was made in cooperation with government and industry. Extensive research, supported by Franki Canada, was made on the compaction of soils and the bearing capacity and settlement of piles. The uplift capacity of foundations under vertical and inclined loads for foundations of transmission towers was investigated in cooperation with Ontario Hydro; extensive research on the strength of steel culverts in sand and clay fills and the composite design of underground structures were supported by ARMCO and the Corrugated Metal Pipe Institute of Canada. In cooperation with the federal Department of Transport (now Transport Canada) an investigation was made of the load carrying capacity of concrete airport pavements and an analysis of the bearing capacity of floating ice sheets for emergency landing strips for aircraft in northern Canada.

Since much of TUNS geotechnical research is of an applied nature the results of the work found their way into geotechnical textbooks and codes of practice in Canada and abroad, such as the *Canadian Foundation Engineering Manual*, *Ontario Highway Bridge Design Code*, and *CSA Specifications* for "Design of Foundations for Fixed Offshore Platforms," the *U.S. Army Engineers Manuals* for "Shallow Foundations" and for "Pile Foundations," and the *U.S. Navy Design Manual* for "Soil Mechanics" (NAVFAC).

1970-1971 Sabbatical Leave

Because of his heavy undergraduate teaching and graduate teaching and research, and his involvement in university administration as Department Head and as Dean of Engineering, Geoff could not take regular sabbatical leaves during the 35 years of his teaching period at the College.

However in 1970 he was granted a special sabbatical of 16 months. He has written of his experiences during this leave and it is included herein as follows: "I was awarded, by NRC, an Exchange Professorship with France to work for the two months of May and June at the famous Ecole des Ponts et Chaussees (J. Kerisel and F. Baguelin) and Ecole Polytechnique (P. Habib) in Paris, where civil engineering had begun in the 18th century. In addition to teaching, in French, my wife and I were given a car and driver, who provided cultural diversions such as theatre and concert tickets, visits to museums and sight seeing excursions. Visits were made to various geotechnical research establishments and interesting construction sites where important developments were noted in field testing by static cone penetration tests, pressuremeter tests, large piles investigations, new methods of stabilizing walls and tunnels by reinforced earth, slurry trench walls and tieback excavations. During this time I also attended at ICE, London, the brilliant Rankine Lecture on "The Influence of Strains in Soil Mechanics" by K.H. Roscoe, who was unfortunately and prematurely killed in a car accident on his return trip home to Cambridge. As a representative of all Meyerhofs I also attended at Heidelberg, Germany, the Meyerhof-Symposium to celebrate the 50th anniversary of my father's Nobel Prize (1922); seven of the 17 active participants in this Symposium were Nobel Laureates. I also visited my upper high school and friends, my home and father's place of work.

"The summer vacations were spent on an interesting Mediterranean cruise during which archeological lectures and visits to Roman and Hellenic sites in Italy, Greece, Turkey, Aegean Islands and Yugoslovia were made, guided by famous British archeologists, who had made some of these excavations themselves in the past! In September the Norwegian Geotechnical Institute (L. Bjerrum and O. Eide) in Oslo introduced me to the latest developments in laboratory and field testing equipment and procedures with transducers, telemetering and computers. I also spent some time in the "Terzaghi Library" where all Terzaghi's geotechnical reports were collected together with his original German and English diaries and, in a safe, his original linen drawings of 1919 and earlier for apparatus to determine the compressibility and consolidation characteristics of clay, its shear strength parameters, unconfined compressive strength, undrained modulus and other mechanical and hydraulic properties. Important construction sites of foundations, earth retaining structures and landslides in quick clays were visited in the Oslo area (E. Dibiagio) and later near the Trondheim Technical University area (N. Janbu). A short boat trip along the fjords of Western Norway to Bergen was followed by a mountain railway journey along glaciers back to Oslo where an invitation for a guest lecture at the Hungarian Academy of Sciences, Budapest, at the Technical University (A. Kedzi and K. Szechy) was briefly followed.

"October was spent in Stockholm at the Royal Institute of Technology (B.B. Broms and N.O. Flodin) where the well known laboratory Swedish cone tests for shallow indentation of clay samples had been developed to estimate the liquid limit and undrained shear strength from empirical correlations. Moreover, early Swedish geotechnical engineers had also constructed there the first laboratory and field vane shear equipment to measure the undrained strength on the horizontal and on the vertical plane by using various diameter/length ratios of the blades. The laboratory of the Swedish State Railways was also visited (Bror G.W.L. Fellenius, son of the famous Wolmar Fellenius who developed the classic circular-arc method of stability analysis). They also built the first foil samplers and piston samplers for practically undisturbed sampling. Of personal interest was a visit to the Royal Theatre where the King of Sweden annually presents the Nobel Prizes and to the City Hall where the subsequent banquet takes place. Again important sites of landslides and of drainage by cardboard wicks near Stockholm and, subsequently, near Chalmers Technical University (S.Hansbo) in Gothenburg were visited.

"During the next month the Federal Institute for Soil Mechanics in the medieval city of Ghent (E.E. de Beer and R.L.P. Carpentier) gave me information about recent Belgian and Dutch developments of static and dynamic cone penetration tests, cell tests for earth pressure estimates, the behavior of compaction piles with an enlarged base of Franki Piles (M. Wallays), deep drainage of granular fills and cuts and tunnels in overconsolidated clays. The large construction of the new container terminal at Antwerp and at Zeebrugge with its liquid gas facilities and flat side slopes, reinforced with traditional reed matting, were also visited followed by the University of Liege (E. Lousberg). In December the even older German medieval city of Aachen with its Technical University (E. Schultze and W. Wittke) made it easy for me to give graduate lectures and advice to the many doctoral students in the large geotechnical department of the University.

"Furthermore their research was of special interest to me because it covered mostly problems of the bearing capacity and settlement of instrumented shallow and deep foundations under special loading conditions in various soils carried out on a large scale in the very well equipped testing laboratories of the department or in the field on similar consulting work. All research (including equipment) of the department was financed by income from consulting, which extended 2 to 3 times the normal period for the doctoral degree. Because of the tripartite departmental structure I was between the professors, assistants and doctoral students. The students had to put a signed request in a box at the wall of the professor's door and wait in their office for a call. In due course they would come, press a button and timidly enter through two padded doors for a brief talk! This was similar at some other West German technical universities visited at that time, Braunschweig, Cologne, Darmstadt, Essen, Karlruhe, Kiel, Munich and Stuttgart. A more enjoyable work for me during that time was to participate in some meetings of the drafting committee for the extensive DIN 1054 on "Shallow Foundations."

"For the Christmas vacation we went to West Berlin to visit my relatives there in the usual cold and snowy weather. We drove by car to pick up an 88 year old aunt in Cologne to drive her on the Autobahn to other relatives for further celebrations in Holland. Close to the German/Dutch border a thick fog caused long multiple collisions on all lanes, unnoticed by my aunt! In good Christmas cheer mutual agreement was quickly found by the drivers in the front and back! January 1971 found us at the well known German Institute for Soil Mechanics in Berlin (H. Muhs and H. Weiss) which is the oldest German geotechnical research establishment. Apart from lectures at the Institute and advice to the many research assistants at the Institute I found that their work was similar to that at the Technical University of Aachen. With large instrumented foundations under special loading conditions and mainly in sand placed in a prepared bed under a heavy concrete reaction tower. I also lectured at the neighbouring Technical University of Berlin (H. Lorenz) where vibration problems of soil exploration by vibrators and explosives, deep soil compaction, the behaviour of engine foundations, and the mechanical effects of earthquakes on structures have been extensively studied in conjunction with the German Institute for Soil Mechanics. Interesting sightseeing trips were made to my lower high school, my home, father's place of work and colleagues' discovery of nuclear fission, also to East Berlin and neighbouring Potsdam still behind the Berlin Wall.

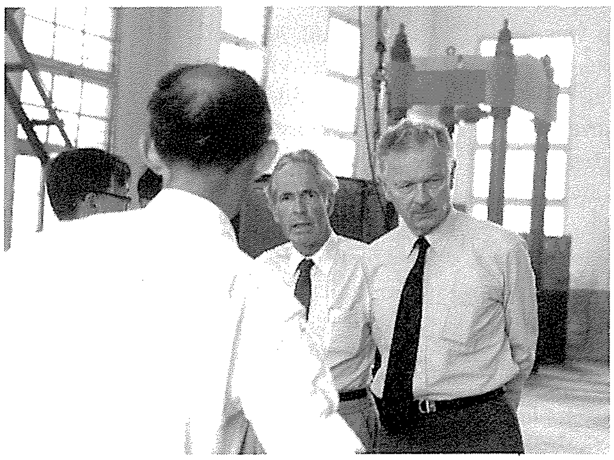
"For the month of February my wife and I accepted a long standing invitation by the Israel Institute of Technology (J.G. Zeitlin and G. Wiseman) of Haifa to visit Israel, and to lecture at the Institute and elsewhere. This, at that time, politically adventurous trip was facilitated by one of my relatives acting as armed bodyguard. Access to the Institute and inside was under strict control. Like its European counterparts this Institute is largely financed by contract research, but additionally by German restitution money. The Institute is well known for its laboratory research in rheology, theoretical plasticity, ultimate load investigations of structures and foundations above and below ground, both onshore and offshore, including dynamic blast loading and radiation effects for defence. Its laboratories and field instrumentation were well equipped with recent European and U.S. apparatus. The Institute suggested a wide range for my daily geotechnical lectures based on previous publications and research in progress, as well as seminars and field visits in the neighbourhood. They also arranged further lectures at some government establishments in other cities and public lectures. Guided visits were made of the many archeological sites, some under active excavation in different parts of the country from the northern borders with Lebanon to the eastern border with Syria to the southern border with Egypt.

"Naturally we were happy to spend some time in Switzerland at the Federal Institute of Technology (R. Haefeli and A. von Moos). The geotechnical department of this Institute became well known in Canada and U.S.S.R. through its pioneering research on the properties of snow and ice, and the establishment of the subject of snow mechanics. I visited an important field station of the Institute which was built in permanent snow high on the slopes of the Titlis Mountain at a funicular railway south of Luzern. There the development, properties and prevention of avalanches and their effect on structures was studied so that economical remedial measures, such as the snow sheds in Western Canada, could be designed to protect highways, railways and canals in mountainous areas. In addition, the creep properties of soils, rocks and detrital materials on embankments and natural slopes were studied; their pressures on several bridge abutments were measured to design remedial measures at different locations in Switzerland, which were visited together with large rock flow slides.

"An important Scandinavian country, Denmark, which had previously been omitted was visited in April for lectures at the Technical Institute of Denmark (J. Brinch Hansen and B. Hansen) in Copenhagen. While the laboratory testing equipment and the method of financing of this Institute was found to be similar to that at the other Scandinavian Institutes, their research was similar to that of the institutes in Berlin and Ghent. In addition important work was done on theoretical plasticity, creep and long term deformation of soils, large scale model tests on foundations and limit state design and partial safety factors in soil mechanics, which originated there and was codified in Denmark in the middle of this century. The Institute is also consultant for the large highway bridges connecting the Danish Islands, Germany and Sweden in the future. The various existing bridges, all of prestressed concrete, for greater economy, were visited.

"During the last months of my sabbatical leave I lectured at various universities and professional organizations in the U.K. In May at an open house of the Building Research Station near London I saw in the Soil Mechanics Division (Len Cooling) their new laboratories and field equipment, completely based on telemetering and computer methods. In a staff seminar with many of my former colleagues I informed them about the geotechnical research at NSTC. I then visited the Transportation Research Laboratory of the Ministry of

Works near London where an interesting exhibition was held about the proposed Channel Tunnel between Dover and Calais. Maps were shown of the geology, geotechnical site investigation and soil tests, full scale tunnel boring machine and linings and the proposed railway cars. Subsequently a brief visit was made to the Dover trial adit of the tunnel. At the ICE, London, I gave a lecture to the British Geotechnical Society on the "Uplift Resistance of Foundations." In the Geotechnical Section (J.R.F. Arthur) of my former University College, I saw the results of true triaxial tests on soils, which differ from those of the standard triaxial tests. Similar results were found in the Geotechnical Section (A.W. Skempton and A.W. Bishop) of the Imperial College of Science and Technology.



G.G.M. visits Geotechnical Laboratory, Nanjing University, (Republic of China. 1986).

"Apart from studying general soil behaviour extensive research was made here on overconsolidated clay, shale, soft and hard rock in very well equipped laboratories, partly in conjunction with large dam constructions in various countries.

"In the Soil Mechanics Section (A.N. Schofield and C.P. Wroth) of the University of Cambridge I had discussions about their development of critical state soil mechanics and saw their special testing equipment. It provides a theoretical limit equilibrium estimate in geotechnical engineering based on idealized failure conditions of the soil. I also saw their new centrifuge for model testing.

"In June I saw two large earth and rockfill dams under construction in Central U.K., where the Building Research Station (A.D.M. Penman) provided instrumentation to check their safety and to measure the deformations. After a brief visit to the Geotechnical Laboratories (P.W. Rowe) of the University of Manchester where large size tests on overconsolidated clays were made, I participated in the Geotechnical Section (J.J. Kolbuszewski and T.K. Chaplin) of the University of Birmingham at an International Symposium on "The Interaction of Structure and Foundation," where many important papers were presented.

"During the next month I lectured in the Geotechnical Section (H.B. Sutherland) of the University of Glasgow. They made large scale instrumented uplift tests on some shafts in the field for the water supply of the City. My lectures dealt with the geotechnical research at NSTC, including the uplift resistance of foundations. In the Department of Civil Engineering (Sir Alfred Pugsley) of the University of Bristol I had a detailed discussion about accident risk treatment and probability concepts of structural failure, which they had originated, and the relationships between safety factors, geotechnical failure probabilities and lifetime probabilities of common experiences. Subsequently the local historic suspension bridge by I.K. Brunel and the new Severn highway suspension bridge by Ralph Freeman were visited. While at the Building Research Station in the 1940's I had made a series of tests on the sandstone rock at the eastern cable anchorages of the Severn bridge. Finally, in the Geotechnical Section (P.K. Banerjee) of the University of Southampton I heard about their recent theoretical analysis of the behaviour of axially and laterally loaded piles in soils. Here my most enjoyable sabbatical leave of 16 months was ended. With my wife (and car) we had a leisurely boat trip in the "S.S.Nieuw Amsterdam" from Southhampton to Halifax, where our sons awaited us at the dockside to drive home."

Later Consulting and Research 1955-Present

Geoff's sabbatical leave of 1970/71 made it possible for him to visit the leading geotechnical researchers and their up-to-date laboratory facilities in Europe and Israel. On his return to Canada he continued his own research and consulting activities with renewed vigor. In the fall of 1976 at Denver, Colorado, he delivered the Eleventh Terzaghi Lecture to the American Society of Civil Engineers that dealt with recent concepts in estimating the bearing capacity and settlement of foundations. At the 47th Canadian Geotechnical Conference at Halifax, Nova Scotia, in 1994, he delivered the R.M. Hardy Keynote Address on "Behaviour of Pile Foundations under Special Loading Conditions." He also became more involved in the use of limit states design for geotechnical design and wrote a number of papers on the subject. As well he delivered the Second Spencer J. Buchanan Lecture at Texas A&M University in 1994 on the topic, "Evolution of Safety Factors and Geotechnical Limit States Design."

He continued to act as a consultant to government agencies, private industry, and to other consulting firms on soil mechanics and foundation engineering problems, e.g. stability of flow slides, Moisie River and at Rimouski, Quebec, for the Quebec Department of Transport; pulp mill at Mulgrave, Nova Scotia; landing of aircraft on floating ice sheets, DOT, Ottawa; bearing capacity and penetration resistance of lunar soils for NASA; foundations for Vancouver International Airport, Sea Island, B.C.; and foundation stability for jackup platform, Cohasset Field, LASMO, Nova Scotia. He was a member of the Environmental Committee, Soil Stability, Disaster of the Ocean Ranger Platform, Newfoundland. He was a consultant for the stability investigations of the marine wharf, Borden and Charlottetown, P.E.I., the berthing dolphins, Halifax and Shelburne Harbours, N.S., the harbour walls, Container Terminals, Halifax, N.S., and the DND Ship Synchrolift, Halifax, N.S. He was a member of the Review Committee, Design Conditions for the Northumberland Straight Crossing, N.B., and the Fixed Link to P.E.I., COGLA, as well as other East Coast Offshore oil and gas developments.

Geoff continues to write publications on geotechnical engineering topics, and to pursue his hobbies, one of which is to travel. During 1996 he celebrated his 80^{th} birthday by flying from New York to Paris on the Concorde aircraft with Susi who was also celebrating her 80th birthday. The flight was a gift from one to the other and an experience that each had anticipated for several years.

Acknowledgments

The preparation of this paper was done with the helpful suggestions and cooperation of Dr.G.G. Meyerhof, who also kindly provided the photographs. The transcript of the interviews with Dr. Meyerhof by Eric Jorden of Geotechnology Ltd. were provided by Eric Jorden. These interviews were carried out in 1983 as part of the proposed Heritage Book on Geotechnical Engineering by the Canadian Geotechnical Society.

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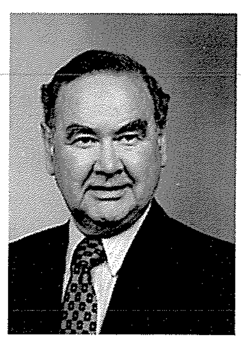
Appendix - Honours and Awards

Geoff Meyerhof's contributions to civil engineering, and to geotechnical engineering in particular, have been recognized by his colleagues, professional organizations, universities, and his country. A listing of some of these awards and honours are as follows:

- 1938 Vernon Harcourt Civil Engineering Prize - London University
- 1954 D.Sc. For Contributions to Soil Mechanics and the Study of Foundations and Structures - London University
- 1973 Dr. Ing. Aachen University - Germany
- 1975 D.es Sc. Ghent University - Belgium
- 1982 D. Eng. Technical University of Nova Scotia - Canada
  D.Sc. McMaster University - Canada
  D.Sc. Queens University - Canada
- 1985 LL.D. Concordia University - Canada
- 1996 Professor Emeritus of Civil Engineering Technical University of Nova Scotia - Canada
- 1953 Research Medal Institution of Structural Engineers - U.K.
- 1958 Duggan Medal Engineering Institute of Canada - Canada
- 1963 Duggan Medal Engineering Institute of Canada - Canada
- 1967 Canadian Centennial Medal - Canada
- 1974 R.F. Legget Award Canadian Geotechnical Society - Canada
- 1977 Engineering Award Association of Professional Engineers of Nova Scotia - Canada
- 1978 Queen's Silver Jubilee Medal - Canada
- 1982 Julian C. Smith Medal Engineering Institute of Canada - Canada
- 1991 Terzaghi Award American Society of Civil Engineers - U.S.A.
- 1945 Fellow Institution of Structural Engineers - U.K.
- 1959 Fellow American Society of Civil Engineers - U.S.A.
- 1962 Fellow Institution of Civil Engineers - U.K.
- 1965 Fellow New York Academy of Sciences - U.S.A.
- 1969 Fellow Royal Society of Canada - Canada
- 1969 Honorary Member Nova Scotia Consulting Engineers Association - Canada
- 1972 Fellow Engineering Institute of Canada - Canada
- 1972 1st President of the Canadian Geotechnical Society (1972-1974) Canada
- 1972 Member International Society for Soil Mechanics and Foundation Engineering - U.K.
- 1979 Honorary Citizen of City of Lima, Peru
- 1981 Life Member Engineering Institute of Canada - Canada
- 1987 Fellow Canadian Academy of Engineering - Canada
- 1991 Life Member Association of Professional Engineers of Nova Scotia - Canada
- 1996 Honorary Life Member German Geotechnical Society - Germany
- 1975 Terzaghi Lecturer American Society of Civil Engineers - U.S.A.
- 1994 Buchanan Lecturer Texas A & M University - U.S.A.
- 1994 R.M. Hardy Lecturer Canadian Geotechnical Society - Canada



LESLIE D. BAIKIE received his engineering degree in 1962 and his Ph.D under Professor G.G.Meyerhof at the Technical University of Nova Scotia.
Dr. Baikie worked as a soils engineer with the Canadian National Railways, Montreal and the Public Works of Canada, Ottawa.
From 1967-80 he was a senior geotechnical engineer and principal with Hardy Associates in Calgary and Burnaby, B.C. He joined TUNS in 1981, where he is Professor of Civil Engineering.

Karl Terzaghi and British Columbia

Charles F. Ripley

The author, a former student of Karl Terzaghi at Harvard University, had the privilege of working with Terzaghi on many of his projects in British Columbia. This paper presents the author's recollections of this association. In so doing, it illustrates the extent and nature of the complex problems that Terzaghi encountered in his work in British Columbia. The author's anecdotes also provide the reader with some insight into the fascinating character of Terzaghi, the father of soil mechanics, now known as geotechnical engineering.

Karl Terzaghi, presented to Charles Ripley, Vancouver, B.C., July 1958.

British Columbia received great benefit from the work of Karl Terzaghi within the province during the period 1945 to 1963. His analytical mind and vast knowledge of case histories gave him the unique capacity to analyse and to provide effective, practical solutions to a variety of complex problems. These included: the arresting of ground movements at the site of the Bridge River Powerhouse #1, the correct analysis of the cause of the landslide that destroyed the Whatshan Powerhouse, the design of the Daisy Lake (Cheakamus) earthdam that was sited on a landslide deposit, the analysis of the causes of the unsatisfactory performance of the Bridge River diversion dam, the design of the storage dam on the Bridge River at a site so complex that only he was capable of undertaking the design, and the design of the Kenney Dam on the Nechako River, the then highest rockfill dam with a sloping core in existence, to mention a few.

An outline of the status and availability of soil engineering services within North America in the 1940's is a prerequisite to appreciation of the contribution that Karl Terzaghi's work in British Columbia made to that province and to Canada. In the 1940's there was no soil testing laboratory on the west coast of Canada, and few if any on the west coast of the U.S., that had the then-current conventional equipment for measurement of the shear strength and consolidation properties of soils. The only two functioning laboratories with such equipment in Canada were at the University of Alberta and at the Prairie Farm Rehabilitation Administration (PFRA), in Saskatoon. Up until 1947, only four Canadian engineers had undertaken the full-time graduate program in Soil Mechanics at Harvard University. All four of these came from the Universities of Alberta and Saskatchewan. They were D.S. Kirkbride, R.M. Hardy, R. Peterson and me, in that order. Likewise there were few, if any, engineering geologists with significant training and experience on large civil engineering works, due to the hiatus of heavy civil construction during and between the two Great Wars.

The beginning of Terzaghi's activities in B.C. in 1945 coincided with the start of a period of unparalleled economic and industrial expansion in North America, and the need for soil engineering services to deal with projects of progressively increasing scale. Up to that time, the need of soil engineering services and the benefit therefrom to the engineering profession and to the construction industry were virtually unknown and unappreciated. His work in B.C. was instrumental in the training of engineers and constructors, thereby uplifting the status of soil engineering in civil works, but it took time.

At Terzaghi's suggestion, I arranged in late 1951 with the Dean of Engineering at U.B.C., for a luncheon meeting with members of his civil engineering staff . The purpose was to urge the university to establish a soil mechanics laboratory. Terzaghi explained to the university representatives that he could foresee sufficient commercial work in B.C. for a modern laboratory to pay for the equipment and operating costs. Hence, in this way, the university could develop a modern soil mechanics laboratory at minimal cost and have it available for student and research use. After a lengthy and friendly discussion, the response of the Civil faculty was negative. It was summed up in a statement to the effect that " the department thought that soil mechanics was technology and that its policy was to teach fundamentals, not technology." Two years passed before the Civil Engineering Department hired Robert Spence and a soil mechanics course was finally introduced.

British Columbia, with its mountains, its verdant forests and its glacially carved coastline, held great fascination for Karl Terzaghi. He relished the challenge of analyzing the effects of the complex quaternary geology, (Terzaghi 1955), on the design and construction of each of the many engineering projects with which he was involved in B.C. The projects ranged from dams to treatment of unstable slopes to the foundations for heavy industrial plants. He recognized that an understanding of the uncertainties that nature presented, both above and beneath the surface of any project site, was essential to the success of a project. Hence he was an avid student of nature, keenly interested in the complex geologic processes of glacial scour and deposition, of the multiple sequences of glacial and fluvial deposition in B.C.'s mountain valleys, of the effects of isostatic and eustatic fluctuations on the marine shorelines of B.C., of the multiple sequences of drowned valley deposits and of quaternary deltaic deposits, (Terzaghi 1962a). As a result of his fascination with these complexities, the majority of the consulting assignments that he was willing to accept from 1945 to 1963 were in B.C.

Consulting Assignments in B.C.

Terzaghi's initial encounter with the compressible drowned valley clays of the coastline of the Pacific Northwest occurred in 1928-29 (Terzaghi and Peck 1948a). These were soft marine clays deposited when ocean levels were higher, and which were subsequently covered by alluvial sands and gravels after the ocean levels had dropped to lower levels. The project was a pulp and paper mill under construction at Hoquiam, Washington, where seemingly inexplicable settlements were occurring. On that project he became acquainted with V.D. Simons, a well-known designer of pulp and paper mills, and his son H.A. Simons. His careful analysis and explanation of the settlements at that site resulted in a strong bond of mutual respect between Terzaghi and H.A. Simons. I believe this was probably the first opportunity that Terzaghi had to test his theory of consolidation against measured settlements of large magnitude over a large area.[1] Several feet of fill had been placed on the building area for site grading purposes. The settlements were the result of consolidation of the underlying drowned valley clays due to the applied fill loads.

When H.A. Simons was engaged to design a pulp and paper mill at Port Alberni, B.C. in 1945, he sought Terzaghi's advice on the location, subsurface investigation and design recommendations for the plant foundations.[2] This first assignment in B.C. undoubtedly aroused Terzaghi's interest in the complexities of the terrain in B.C. As at Hoquiam, each of the proposed sites involved site preparation fill above underlying compressible drowned valley clays, that were sandwiched between fluvial deposits. Site selection was made on the basis of a few testholes supplemented by numerous inexpensive penetration tests (Terzaghi 1953a, 1957a). The latter consisted of the driving of steel rails with a pile driver to indicate anomalies and depths for support on piles (Terzaghi and Peck 1948b).

Similar engagements of Terzaghi were made by H.A. Simons in 1948 and 1951 in connection with new pulp and paper mills near Nanaimo and Campbell River, B.C.

In 1949 Terzaghi was retained by the International Engineering Co. Inc., (lECO), to make a reconnaissance of proposed damsites on the Nechako River, relative to the subsequent Kemano-Kitimat power and aluminum smelter project of the Aluminum Company of Canada, Ltd. (Alcan).[3] On this and the Port Alberni pulp mill project, Terzaghi became acquainted with Victor Dolmage, the eminent engineering geologist in B.C., with whom he became a close friend.

Subsequently in 1950, when Dolmage was retained by the B.C. Electric Co. to investigate movements of the slope above Seton Lake, on which the Bridge River Powerhouse #1 was founded, he persuaded the Utility to retain Terzaghi, to investigate the cause and to develop a program to arrest the slope movements[4] (Terzaghi 1953a, 1957b).

In 1951 Terzaghi was retained by the Stone and Webster Engineering Co., to assess and advise on a potential problem that was related to the Waneta Dam, then under construction on the Pend d'Oreille River, near Trail B.C. Adjacent to the dam was a deep buried valley that joined the Columbia River valley downstream of the dam. Downstream leakage through the pervious deposits in the buried valley posed a serious threat of slope instability along the Columbia River, where the buried valley joined the Columbia. Such instability would disrupt an important rail line along the Columbia. In order to control harmful leakage, Terzaghi designed an innovative vertical drainage curtain across the buried valley, consisting of a series of tunnels, one above the other, that were backfilled with sand and gravel, in order to intercept any leakage (1953a).

Also in 1951, Terzaghi was retained again by IECO concerning the design and construction of the Kenney Dam on the Nechako River, near Vanderhoof B.C. This is a 317 ft. high, sloping core rockfill dam for storage and diversion of water for the Alcan Kemano-Kitimat project.[5]

When I initiated my consulting practice in B.C. in 1951, I was unaware of the relationships that Terzaghi had developed with Simons and with the B.C. Electric Co. In June 1951, Arthur Casagrande was in Vancouver and had a few free days between meetings with clients. He contacted me, his former student, and suggested that he spend a relaxing day or two with me. During his visit, I mentioned the large-scale landslides that were a chronic problem to the C.N. and C.P. Railways in the Thompson River Valley (Stanton 1897, Cartwright 1909). Casagrande said that he and Terzaghi would be in Vancouver for client meetings in July, and that he and Terzaghi would be interested in examining the area, with no obligation to the Railways. Arrangements were made for such a field trip in a C.N. private rail car with Terzaghi, Casagrande, the C.N. district engineer and Ripley present (Terzaghi 1957b). During the trip, I mentioned that I had accompanied the Chief Engineer and District Engineer of the C.N.R., on a reconnaissance visit to the area in April, and showed my report to Terzaghi. He examined the report and then promptly asked me if I had dictated it. With later hindsight, I came to appreciate that Terzaghi's seemingly critical comment was really a friendly constructive comment, emphasizing the need for a consultant to take great care always in preparing his report.

At Cheakamus Dam site, B.C. from left: Mark Olsen, Charles Ripley, Alan Fletcher (B.C. Electric), Victor Dolmage, 1954.

On completion of the field trip, a meeting was held with senior officials of the C.N.R. in Vancouver, at which Terzaghi explained that in order for effective stabilization of the slide areas to be developed, a program of test holes, laboratory tests and stability calculations would be required. The District Engineer, who had attempted to deal with the instability for decades, was very receptive. However the Chief Engineer was not receptive, and the problems have continued to be dealt with as a periodic maintenance problem.

In the autumn of 1951, I received, "out of the blue," a copy of a letter from Terzaghi to IECO. It stated that the report of some laboratory soil tests that had been requested by Terzaghi, was not worth the paper on which it was written, with clearly stated reasons why. By copy to me, Terzaghi was letting me know of the care needed for some tests that he would be requesting from me on a different project. The unsatisfactory tests, of which I had no knowledge, had been done at a concrete testing laboratory in Vancouver. A few months later a copy of a second letter from Terzaghi[6] to the laboratory, contained the statement: "I am glad you have finally succeeded in making the tests as they should have been to start with... I am sending a copy of this letter to Mr. Ripley because he will have to prepare for me in the near future, the results of his tests on the Seton Lake samples, whereby he should take the content of this letter to you into consideration."

A copy of a third Terzaghi letter, was addressed to the local manager of IECO at the start of fill placement at Kenney Dam in the spring of 1952, following a visit by Terzaghi to the site. It stated that the work of the fill inspection staff was inadequate and recommended that the manager arrange immediately for me to go to the site to train the fill inspectors. Fortunately the principal of the fill inspection company was immediately made aware of the letter and he promptly attended to the matter himself. This was Terzaghi's way of getting a message across and of getting the results that he desired.

Two slope instability problems in B.C. in 1953 received the benefit of Terzaghi's review. They were a landslide that had disrupted the P.G.E. Railway near Quesnel, B.C., and a landslide that had destroyed the Whatshan Powerhouse of the B.C. Power Commission, due to leakage from a pressure tunnel.[7]

Terzaghi's engagements in B.C. in 1954 included the review of the suitability of two sites for a paper converting plant for Simons, and of proposed sites for the Daisy Lake Dam (formerly Cheakamus Dam) for B.C. Electric. In the latter case, Terzaghi's commission was expanded to include direction of the site investigations, design of the earthdam, and review of the construction through the years 1954 to 1957, (Terzaghi 1957c, 1960). In the former case, he reviewed the design, construction and performance of the foundations, after a final site had been selected, (Terzaghi 1961b). This was the first project on which Simons had retained me. In hindsight, my detailed involvement in the foundation engineering for the paper converting plant was a trial of my competence by Simons. Shortly thereafter, Terzaghi told me that he had advised Simons to retain me to undertake the detailed foundation engineering on several upcoming pulp and paper mill projects, and that he would be available only in a review capacity. Thereafter, the foundation engineering for the sites of many new mills and mill expansions, in B.C. and elsewhere, were handled in this manner. In B.C. they included new mills at Crofton in 1956, at Castlegar in 1958, mill expansions at Campbell River and Port Alberni, and several others in later years.

In 1955 Terzaghi's engagements included the investigation and report on the cause of a marine landslide in Howe Sound at Woodfibre,[8] and the site investigations for the storage dam on the Bridge River (formerly Mission Dam). The storage dam was ultimately renamed Terzaghi Dam in his honor. His early work on this project involved a detailed analysis and report on the causes of the defective performance of the Bridge River diversion dam. The diversion dam had been built in the late 1940s[9] and was to become part of the storage dam. The subsurface conditions beneath the proposed storage dam were particularly challenging and difficult, (Terzaghi and Lacroix 1964). Nevertheless, at the age of 73, he willingly and with confidence undertook the design of the storage dam in 1956, probably the greatest challenge of his illustrious career. As was his practice, he visited the site several times a year through the investigation, design and construction periods until 1960, when, for health reasons, he was no longer able to travel.

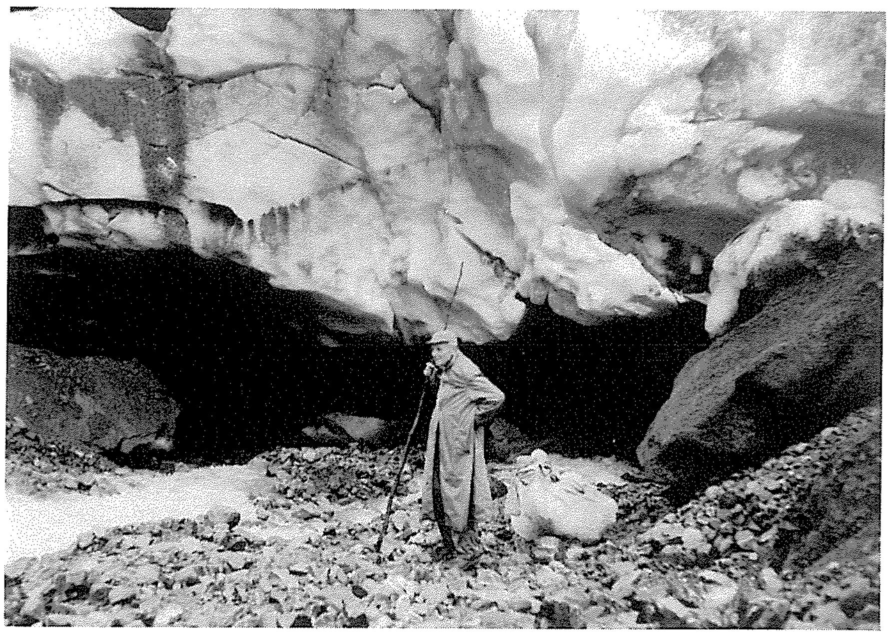
In 1959, I was successful in persuading Terzaghi to accept an assignment to review and advise on the treatment of the seepage condition at the left abutment of Cleveland Dam on the Capilano River, for the Greater Vancouver Water District (GVWD). I had been involved with this complex problem since 1954, prior to the filling of the reservoir in the winter of 1954-55. When I described the condition to Terzaghi and asked if he would undertake a review of the condition, Terzaghi promptly replied that he would be delighted to do so, but only as soon as 10 years of the performance monitoring records could be made available, in order to have a sound basis for an analysis.

Fortunately, he subsequently relented and agreed to become involved much sooner, in 1959.[10]

He continued to advise on the design of the abutment drainage measures and to analyze the performance through January 1963,[11] the last year of his life.

Also in 1959, he agreed to participate in the design of the earthdam portion of the Seymour Falls Dam, for the GVWD. The challenge of this project was the design of measures to control seepage through a foundation that was both pervious and compressible (Ripley and Campbell 1964).

His days of travel ended in 1960, when he had a leg removed. He continued to advise on two Canadian dam projects until 1963, the year of his death. They were the Cleveland Dam in B.C. and the Gardiner Dam in Saskatchewan.



Karl Terzaghi at Salmon Glacier, Stewart, B.C., Summer 1956.

Terzaghi the Engineer

Terzaghi is rightly credited with being the founder of the science of soil mechanics, and he remained the undisputed leader in this field throughout his life. His early achievements caused him to recognize that he was unusually gifted, and that he should devote and limit his activities only to research and to engineering practice that expanded the field of knowledge. In his own words in 1955: "I rarely accepted a consulting assignment unless there were unusual difficulties involved or an accident had already occurred. Therefore I had unusual opportunities to become acquainted with the hazards and uncertainties involved in earthwork and tunnel engineering. Condensed records of my observations and conclusions have been published in about 160 professional papers and four books."[12] Hence he would not accept assignments that he felt were routine. Instead he would refer the client to his former students and other engineers in whom he had confidence.

On each of his assignments in B.C. and elsewhere, he would not accept any limitation on the amount of time that he would need to complete the assignment. He carried out frequent site visits during the construction of the projects which he had designed and on which he had reported. This was done so as to be aware of variations in field conditions from those that he had assumed, and to make the necessary design changes.

Moreover, his site visits were necessary to give him an opportunity to determine if the inspection staff and the constructor were achieving his design intent. His site visits would involve discussions not only with the engineering staff, but with the constructor's supervisor also, so that he would be aware of any unnecessary and unusually stringent features of the design from a construction viewpoint. If so, he would modify the design to better suit construction limitations as long as his design intent was assured. With the realization that his site visits gave an incomplete picture, he welcomed open discussion in the field with the inspection staff and the constructor.

On complex projects such as the Daisy Lake (Cheakamus) and Terzaghi Dams, he insisted on having one or more representatives of his choice on site throughout the construction. He gave specific instructions to his representatives as to their function and authority. They were required to send detailed weekly reports to him and thereby be his eyes and ears about the progress of the project and the problems being met. He would send his comments and criticisms of these reports to the inspectors so that they could more effectively perform their tasks. Mark Olsen of my staff served as Terzaghi's senior representative on the Daisy Lake and Terzaghi Dams.

Terzaghi was very conscious of cost and efficiency in the economic use of construction materials on his projects. Examples of this characteristic were his use of local pitrun materials and innovative construction procedures at the Terzaghi, Daisy Lake and Seymour Falls Dams. For each of these dams, he appreciated that the construction difficulties and requirements could not be depicted accurately in the contract documents.

Hence, in order to facilitate adaptation of the design to suit unforeseeable subsurface conditions that would only be revealed when the site was opened up, he recommended that the contracts be arranged on a force account basis; otherwise the owner could be faced with overly conservative bids, and/or the likelihood of litigation over construction extras. In each case, this arrangement resulted in significantly lower cost than if the construction had been based on a total sum contract at unit bid prices.

In Mark Olsen's words, "Terzaghi was a relentless pursuer of information." He kept himself aware of new and innovative construction equipment and methods used in earthwork engineering and of case histories of projects involving failures. He did this by extensive literature search and reading of technical journals, as well as by consultation with the constructors with whom he had previously worked and with those on his current jobs.

He personally examined the soils and rock that would be encountered on his projects, not relying solely on the descriptions and laboratory test results presented by others in reports to him. He searched out and reviewed published geologic reports on each project area. In many cases he consulted a competent geologist who was local to the project region.

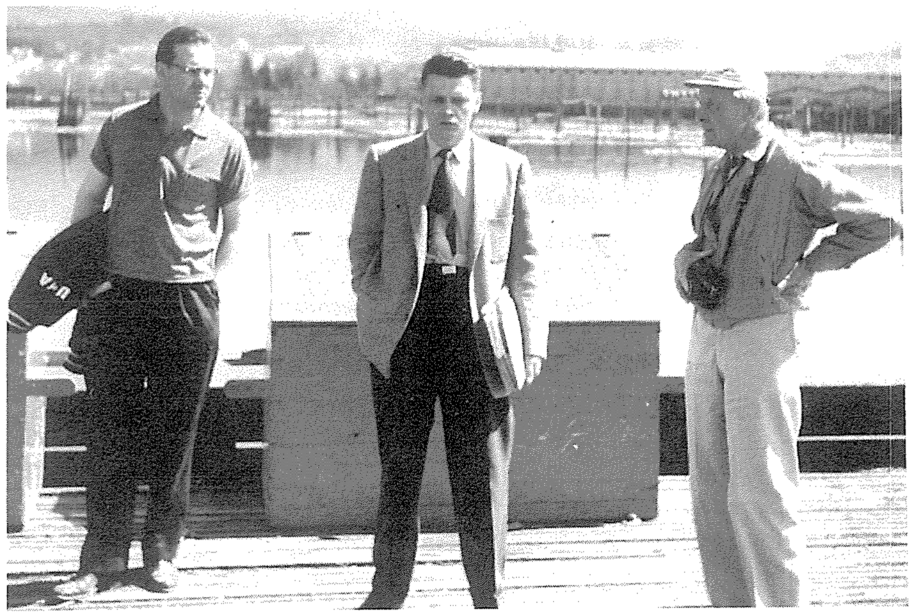
His visits to British Columbia were usually about a week long. He would spend from Monday to Friday on B.C. Electric projects, with two days in the field. The remainder was spent in discussions in Vancouver with the project design engineers, and in writing his report.

On each visit he always filed a report setting out his observations and recommendations to B.C. Electric, usually on Friday. Saturdays and Sundays were usually spent on Simons' pulp and paper mill projects: meetings at Simons' office on Saturday morning and a field trip to the mill sites on Saturday afternoon and Sunday with Earle Klohn and myself. On these projects he relied on me to file a report on his observations and recommendations to Simons.

His remarkable memory permitted him at all times to draw up an example of a particular point from his vast knowledge of case histories. That knowledge must have been derived not only from personal experience but also from a lifetime of literature search and analyzing case histories, and cataloguing them in his mind.

His power of concentration was enormous, which accounted for the fact that he resisted interruption of his thought when working on a project or a paper, in his office or in the field.

His periods of concentration in the field were visibly apparent to those with him. They learned to wait until he relaxed his concentration, which again was visibly apparent, before initiating discussion.

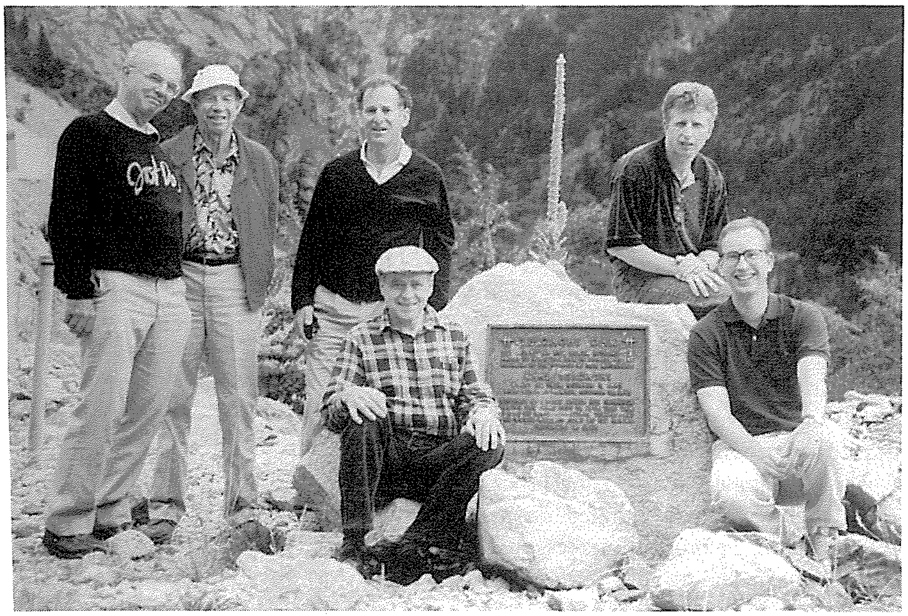


At Port Alberni, B.C. pulp mill, from left: Ian Morrison, Earle Klohn, Karl Terzaghi, April 20, 1957.

Terzaghi the Person

The outstanding characteristics of his personality that I observed were his self-discipline, his powers of observation and analysis, and a remarkable memory. His self-discipline was evident in many forms. He carefully selected his activities so as to devote maximum energy to his work and to his research. He accepted only a few assignments at any one time, even though his services were widely sought by innumerable engineers and organizations. He considered it an obligation at the end of each assignment, to take the time to thoroughly study and condense the new information he had learned from the project, and to present that in a paper. He urged others to do the same, in his words "to sort the raisins from the rice pudding." Of course there was no remuneration for such time-consuming effort, but he was not interested in accumulating wealth. His per diem rates were comparatively high, one of the reasons for which he explained to a Vancouver client "was so that clients would pay appropriate attention to his recommendations." Self-discipline led him to be uncompromising when he knew that his recommendations were correct and the client would not heed them. At one project in eastern Canada, he resigned when the owner balked at installing drainage to relieve artesian pressures beneath the site. The owner regretfully pleaded for his return after the artesian pressures caused a landslide that destroyed the site, at great financial loss.

Terzaghi's lifestyle was one of simplicity, frugality and practicality. The hotel he stayed at in Vancouver was the Devonshire, a small modest hotel, diagonally across from the prestigious Hotel Vancouver. The hotel staff came to know his needs. They always gave him a room with a north view toward the mountains. It had a "Murphy bed" that folded into the wall, so that he had plenty of work space during the day. They provided him with a folding table consisting of a large sheet of plywood supported on sawhorses, so that he could spread out large drawings during the day.



Cairn dedicating Terzaghi Dam, from left: Mark Olsen, Charles Ripley, Richard Goodman, Cyril Leonoff, Bryan Watts, Peter Brown (B.C. Hydro), August 10, 1993.

His activities in non-working hours were carefully selected. He avoided social functions in favor of a quiet time in natural surroundings. In Vancouver, he usually had his meals alone. When he had finished work in the evening at his hotel, he loved to walk in Stanley Park. On site visits to Cleveland and Seymour Dams he would take time for a walk among the large trees at Cleveland and within the moss-laden cedar rain-forest at Seymour. Each trip to Port Alberni included a stroll through the virgin rain forest at Cathedral Grove. He spent a vacation hiking in Mt. Robson Park, studying the morainal deposits at and downstream of the glacier terminus. In the company of M.J. Hvorslev, others, and myself he spent several days in the area of the Salmon Glacier near Stewart B.C., studying the glacier and glacial deposits. If he had a spare day in Vancouver, he would hike on the mountains of North Vancouver.

Further evidence of his self-discipline was his slow deliberation on a matter, as opposed to reaching decisions quickly. He appeared to silently analyse his thoughts from more than one point of view before making a comment or stating his opinion. In meetings with my staff and the client he was not autocratic, but would willingly change his opinion if presented with evidence to the contrary. He relied on those providing him with data to brief him fully and honestly, and to correct any misunderstanding that he may have had about an issue.

He initiated a procedure that continued through the 1950s, whereby he would have me meet him on arrival at the Vancouver airport and drive him to his hotel, and then drive him to the airport for his departure. This was a much appreciated opportunity for discussion with him of my current projects, in which Terzaghi invariably showed great interest. Despite the difference in his age from that of Klohn and me, travelling and working with him were a joy and pleasure for all. He was relaxed, humorous and liked to tease and chide those with him. At work and leisure, he was very even-tempered, an indication of his self-discipline. All comments and criticisms that he made were always direct and delivered in an even tone. Obfuscation was foreign to him. Two maxims that he imparted to me in meetings with clients were typical of his outlook. One was "the sooner you get to the truth of a situation, the better for you and for your client." The other was "your proposed solution is far too complicated. If it isn't simple, it is unlikely to be any good." Like his friend Dolmage, he was a great raconteur, and could come up with a joke appropriate to almost any occasion.

Terzaghi showed great interest in people he met who were dedicated and accomplished in their work, whether they were "blue or white collared." He admired a drill foreman, Ralph Smith, for his ingenuity, good sense and reliability in his work. He admired also, Smith's wife, a hearty drill camp cook as being an ideal wife for a driller who spent most of his life in the bush. He admired George Smith, a burly surveyor who had run an accurate set of levels over the rugged Coast Range of mountains in B.C. He admired H.A. Simons for his dedication to superior engineering. He also admired a good memory in others. He admired two colleagues, Messrs. A. Ackerman and D. Bleifuss, in each case for taking an unpopular stand at great personal sacrifice against policies that compromised their ethics (Terzaghi 1962b). He showed great compassion for a colleague, Dr. Andre Coyne in a warm and consoling letter to him after the collapse of the Malpasset Dam.

Summary

Terzaghi's contribution to B.C., and to Canada as well, has been much greater than the solutions that he provided on his many B.C. projects. He opened the path for due recognition of the place of soil engineering in civil engineering practice. His work demonstrated many critical aspects of Soil Engineering in B.C. the importance of recognizing the potential for heterogeneous stratification in the deposits of our glaciated river valleys and the effects of such heterogeneity on the performance of structures founded on them, as illustrated by the site of the Terzaghi Dam (Terzaghi and Lacroix 1964), and the pulp and paper mill at Port Alberni,[2] the importance of special attention to details in the construction of dams, as illustrated by the jetting by firehose of the sand filter, at the contact zone of the filter with the adjoining drain layer at Kenney Dam,[5] the importance of follow-through inspection of the construction of a geotechnical engineer's design to ensure that the design is modified to account for unforeseeable subsurface conditions revealed during construction, as illustrated at the Terzaghi, Daisy Lake and Seymour Falls Dams (Terzaghi and Lacroix 1964, Terzaghi 1960, and Ripley and Campbell, 1964); the necessity of monitoring and analysis of the performance of a project, as illustrated with regard to the installation of piles at Port Alberni (Klohn 1963), and the abutment seepage at Cleveland Dam;[11] the necessity of prompt investigation and analysis of the cause of the defective performance of a project, as illustrated by the destruction of the Whatshan Powerhouse,[7] where such action was not taken; and the importance and limitations of his observational method. Through his books (Terzaghi 1943, Terzaghi and Peck 1948), his professional reports[1-11] his particularly pertinent papers, (Terzaghi 1944, 1950, 1951, 1953a, 1953b, 1953d, 1954, 1955, 1956a, 1956b, 1957d, 1958, 1959, 1960, 1961a, 1964), and his formal discussions (Terzaghi 1953c, 1957a, 1957b, 1957c, 1961b, 1962a, 1962b), he has made clear the limitations of theory and laboratory testing in the prediction of soil behavior, due to the inherent variations in natural and even man- made soil deposits. He left a pool of well-trained soil engineers and technicians, who were capable of using the procedures that were demonstrated on his B.C. projects, in order to make sound judgements in dealing with the complex soil conditions, not only in B.C. but elsewhere. My staff and I are deeply appreciative of the privilege of the contacts that we had with him on thirteen projects from 1951 to 1963. For those engineers who did not have the good fortune either to know him or to work with him, his papers and his lifestyle will continue to provide in perpetuity, a role model for excellence in engineering.

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CHARLES F. RIPLEY, born in Lethbridge, Alberta, obtained his civil engineering degree at the University of Alberta in 1944 under Professors I.F. Morrison and R.M. Hardy. He took graduate soil mechanics studies at Harvard University under professors Arthur Casagrande and Karl Terzaghi.

From 1944-51, with the Prairie Farm Rehabilitation Administration, Ripley was senior assistant to Bob Peterson on the design and construction of irrigation dam projects in the Prairie Provinces. In 1951 her founded Ripley and Associates in Vancouver, one of the earliest soil mechanics consulting firms in Canada, and was president of its successor, Ripley, Klohn & Leonoff to 1970.

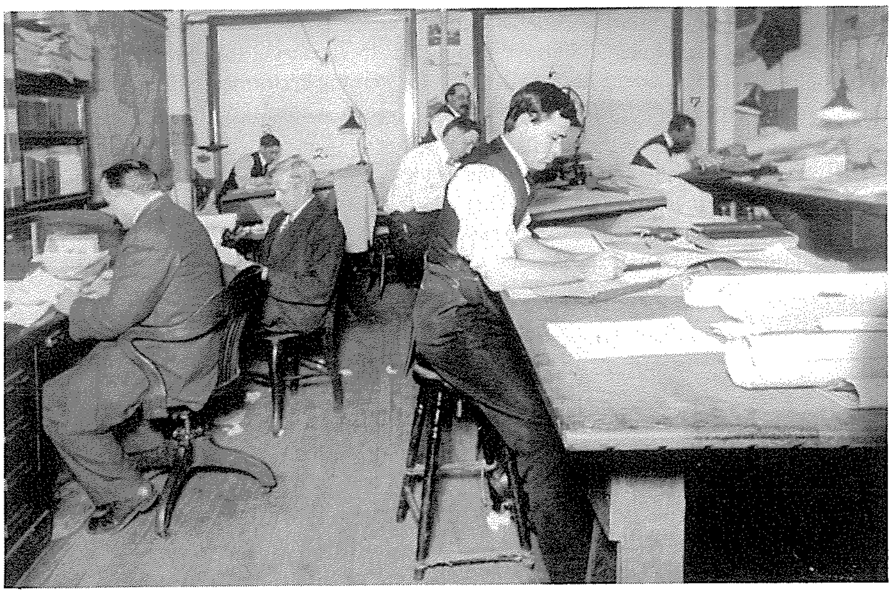
He consulted on the ALCAN Kitimat smelter, on several pulp and paper mills for H.A. Simons, and on water supply dams and the Iona Sewage Treatment Plant for the Greater Vancouver Water, Sewerage and Drainage Districts.

Mr. Ripley has authored case histories on the performance of industrial plants and dams and has been the recipient of the Gzowski Medal for outstanding paper in civil engineering. He has participated actively in engineering organizations. As representative of the PFRA, he attended the first Canadian Soil Mechanics Conference held in 1947 in Ottawa. He was founder of the Vancouver Soils Group in 1953, and a founding member of the Victoria Geotechnical Society. Among other honours, in 1996 Ripley was the inaugural recipient of the Vancouver Geotechnical Society Award.

Reminiscences of an American Geotechnical Engineer Consulting in Canada

Ralph B. Peck

The title of this paper was assigned by the Jubilee Committee. Taking it at face value, I have recounted five episodes that have little in common except that they occurred in Canada over a period of some 84 years. Though never a Canadian citizen, because my parents registered me promptly with the American consul, every return to the country of my birth has seemed like a homecoming.



1. Grand Trunk Pacific bridge design office. O. K. Peck in right foreground. J. G. Legrand at desk to left.

Episode 1 - Origins

It was the panic of 1907 that planted my roots in Canada. My father, O. K. Peck, the son of a Dakota Territory farmer and Sunday-school missionary, worked his way to an engineering degree at the University of Wisconsin that year, only to find a shrinking job market in his chosen field of railroad bridge engineering. After two brief positions with the Minneapolis Steel and Machinery Co. and the Northern Pacific Railway, he and my mother moved in 1910 to Winnipeg where the Grand Trunk Pacific was designing its line to Prince Rupert. First as a bridge checker and then as assistant bridge engineer, he worked on the design of the line's steel bridges (I still have the notebooks into which he entered the stress diagrams) under the direction, in his words, of "an old-country French engineer named Legrand." Legrand was a sound engineer for whom my father had a great respect and who, when the design phase was over, recommended him to the Dominion Bridge Company to take charge of the design and erection of the Provencher Avenue double-leaf bascule over the Red River in Winnipeg. On completion of that project, my father became assistant bridge engineer of the Louisville and Nashville, and the family returned to the U.S. in 1918, during the Great War. At that time, I was six years old.

I have only a few recollections of those first six years, one of being nearly terrified when my Dad tucked me under his arm and treated me to a tour of the steelwork being erected over the river on Provencher Avenue. Another was of evenings with friends at home, many from the old country, singing folk songs. Dad played the piano with some skill, but what he really enjoyed was using his deep double-bass voice. The family friends I remember were mostly English and Scottish. They remained close for many years.

I was a little too young to remember the failure of the Transcona elevator in 1913, but I like to think it must have had some influence on my subconscious. I was not too young, however, to remember how snow squeaks when walked on at -40°, or to remember the huge icicles that remained all winter on the facade of the Hudson's Bay store after it was ravaged by fire in the depths of winter.

My father, although he remained active as Engineer of Structures for the Denver and Rio Grande RR until he retired at age 74, never saw the completed GTP bridges he designed. But in March 1959 on one of my early trips to the site of Portage Mountain (Bennett) Dam, when it was still possible to travel by train to Prince George, I arranged a layover in order to take photographs of the Fraser River bridge.

He was keen to see the use of the cantilever brackets on each side for highway traffic, even though the 1959 loading was far greater than that expected in 1915. Earlier, in 1954, I had photographed the Provencher Avenue bridge and informed him that the bascule had never been used, inasmuch as the hoped-for navigation on the Red River failed to materialize.

Episode 2 - Excitement on the Rails

In 1945 the Association of American Railroads entered into a research project with the University of Illinois to study railroad roadbed stabilization. In the early years of the work, attention was focused on various means for preventing or repairing soft spots in the roadbed that developed under the repeated passage of trains. Later, however, the work included the study and remediation of various landslides experienced by the member railroads. Inasmuch as the Association of American Railroads included the railroads not only of the United States but also of Mexico and Canada, the Canadian railroads participated actively in the program. In August 1954 we were invited to inspect the line of the Canadian Pacific through the Thompson River Canyon between Ashcroft and Lytton, British Columbia. The canyon, presently in arid country, had once been filled with glacial lake sediments consisting almost entirely of coarsely varved or banded silts. The river had cut through the silts leaving great terraces at several levels now high above the river bed. The Canadian Pacific had established its line near the base of the silts, which formed cliffs high above the roadbed, in 1882. Its engineers had chosen the most favorable side of the river. Much later the Canadian National, seeking its entry into Vancouver, generally occupied the land along the opposite side of the river, although in some places available space was inadequate and both railroads were located on the same side.

When the Canadian Pacific was built, the slopes leading up to the terraces seemed stable, but as time passed, great landslides developed at intervals of time that seemed to be getting shorter. The slides became a serious threat to the operation of the railroad, and we were invited by the Canadian Pacific to join the long list of engineers and geologists who had studied the situation.

Arrangements were made for our group to traverse the slide area in a motorcar of the type used by inspectors and section gangs in carrying out their work. The movement of such cars was, of course, under the control of the train dispatcher. Since we had proper clearance, we were more than a little shocked to round a curve and see the locomotive of a freight train bearing down on us at a most uncomfortable speed.

The railroaders stopped the motorcar as quickly as possible and struggled to get it off the track while we non-railroaders were happy to get out of their way. It looked to be a close call, when one of the CPR employees suddenly abandoned the effort and shouted that the train was on the CN tracks which, at this location, closely paralleled the CP. The CN engineer waved a cheery greeting as he went by with a broad grin, and we, rather shaken, got our car back on the track and continued.

On the next day we met with the CP engineers in Vancouver to review the extensive records of the slides and to obtain geological background from Victor Dolmage, already recognized as the dean of engineering geologists in the province. This meeting began a long and most pleasant relationship with a great geologist and a warm and gracious personality.

There appeared to be no question that the slides became active only after the construction of the railroad and that the activity increased during the first few decades after construction. Yet, the railroad did not cause the slides. What the railroad did was to open the area to settlement. Farmers found the nearly level terraces to be remarkably fertile and developed irrigation systems to bring water to their lands. It was the irrigation water that caused the instability.

If such a project were to be undertaken today, no doubt the environmental impact studies that would have preceded it would have foreseen the consequences. Perhaps, if such environmental concerns had prevailed in the late 1800's, the railroad project might have been stopped. Yet, without it, there probably would have been no Canada.

2. Group inspecting rock conditions at bottom of Lower Notch

Episode 3 - Lower Notch

One of the most unusual dams in Canada is Lower Notch on the Montreal River near its mouth in Lake Temiskaming. Only 160 ft high above the river bed, it stands 400 ft above its bedrock foundation, one of the highest dams in Canada. The dam is located in a narrow bedrock gorge originally filled with sediments having a thickness of some

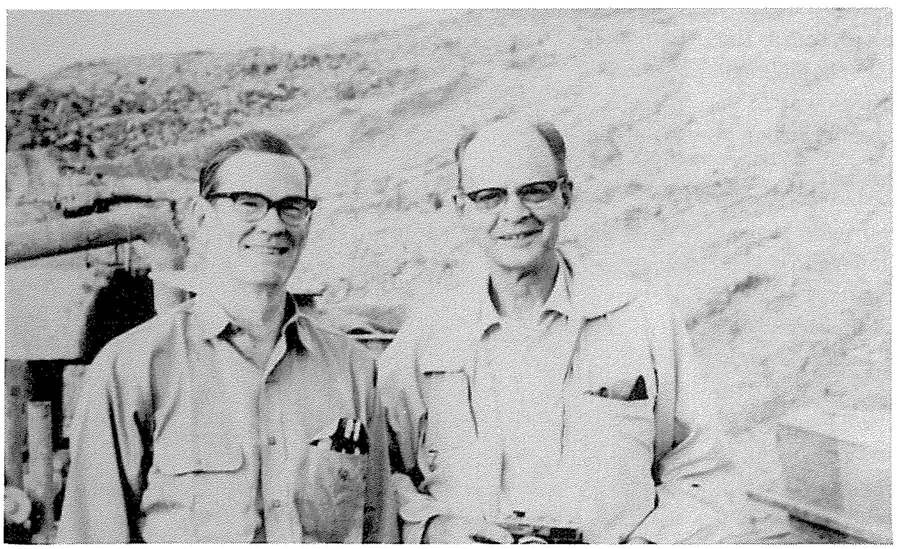
300 feet. The principal design question was whether to construct the embankment on top of the heavily consolidated valley fill, or to excavate at least the core section to bedrock obviously the more expensive alternative.

When Ontario Hydro introduced me to the project, enough preliminary exploration had been done to establish the nature of the valley fill and to recognize the likelihood of near-vertical relief joints in the rock parallel to the sides of the gorge. These joints, whether empty or filled with sediments, provided potential passages for seepage or flow that might attack the valley fill, erode it, and quickly lead to failure. Yet, leaving the valley sediments in place was so attractive economically that I was keen to consider some means to do so.

Since the site was close to a hard-rock mining district, I thought local talent might be available to sink two shafts on the axis of the dam, one at each end, a few feet back from the canyon wall. Horizontal drill holes to the canyon wall would intersect any vertical joints, and the joints could be washed out and grouted. In this way the valley fill could be protected from erosion.

Ontario Hydro shortly engaged Acres as the designer, whereupon Acres proposed to engage a Board of Consultants. I was appointed to the Board, along with Don MacDonald and Arthur Casagrande (who had taught me and so many others about soil mechanics and earth dams). My proposal was looked on with less than enthusiasm, and the design was developed with a till cutoff placed in the excavated gorge. I was not reluctant, because I recognized the uncertainties in my proposal.

The excavation was a major undertaking, not only because it was so narrow and deep, but because of the extensive dewatering to dry up the lowermost, highly pervious part of the valley fill. When it was accomplished and we consultants stood at the bottom of what seemed like a small replica of the Royal Gorge, Arthur turned to me and said, "You know, I think we could have left the valley fill in place." But, impressed by the vertical open joints that were all too evident, I had to reply, "I was just thinking how glad I am that we decided not to."



3. With Arthur Casagrande at Lower Notch.

The till borrow for the core was already slightly wet of optimum, and to make matters worse the weather when the lower part of the core was being placed was unusually wet. The deep excavation proved to be a huge bathtub that collected all the rainwater at the bottom where the core was being placed and compacted.

Often, surface drainage and pumping could not prevent the most recently placed lifts from getting soaked, so the material had to be removed and replaced. Not infrequently, the weekly reports showed negative progress. Nonetheless, persistence paid off, and the dam stands against well treated rock with its core tightly sealed.

Episode 4 - The Great Windsor Sinkhole

In 1945 I was asked to investigate some very large settlements of the buildings in an industrial plant on the U.S. side of the Detroit River. The problem seemed to be a textbook example of consolidation of soft Detroit clay overlying the limestone bedrock located at a depth of about 65 feet. Just above the rock was a thin permeable granular deposit in which the piezometric level had been lowered to the base of the clay by leakage into the casings of deep wells that had been installed beneath the plant to recover salt from deposits several hundred feet below the bedrock surface. On the basis of what appeared to be reasonable assumptions I could demonstrate that the observed settlements were of the same order as ones that could be calculated by consolidation theory.

On his regular visits to lecture at Illinois, Terzaghi routinely quizzed me about my consulting jobs. When he read my report on this one, he informed me very gravely that I had completely missed the boat. He was certain that solution cavities had developed in the salt during decades of extraction, that the roofs of the cavities had been collapsing or sagging, and that there was danger of the formation of a sinkhole that might engulf part of the plant.

When I conveyed this information to the chief engineer, whose background was in chemical processing, his reactions ranged from incredulity to panic, but he faced the situation by setting up a three-person board, chaired by Terzaghi, with myself and a well-known geophysicist. After several years of settlement observations, mapping of the cavities by means of a device developed by the geophysicist, and development of a new brine field beneath an area unoccupied by structures, the situation came under control.

During this time the mechanics of the settlement passed from a state of great secrecy, because of the issues of safety and potential liability involved, to one of awareness and public regulation.

The salt beds beneath the U.S. side of the Detroit River extended, of course, beneath the Canadian side and had been similarly exploited. My client's officials had friendly relations with those of their counterpart company in Windsor and called their attention to the problem and the investigations going on. The reaction was that they were unaware of any settlements and felt no concern. Nevertheless, during one of our Board meetings, a trip to visit the Canadian plant was added to our agenda. We pointed out many signs of settlement and described the program in progress across the river, were politely thanked, and for several years heard no more. Then, suddenly, in February 1954, the whole world heard about the great Windsor sinkhole. It was the cover story on *Life Magazine* and made headlines across the U.S. and Canada.

The ensuing inquiry, in which I had a small part, found that the company had indeed followed up on some of the suggestions made by their visitors from the other side of the river. They had started a program of settlement observations, and one of their engineers had systematically plotted the results as contours of settlement. The contours showed that a depression was growing wider and deeper, and as the depression deepened the engineer had colored the deepest closed contour in red and carefully put the successive maps in his files. He had accumulated a beautiful set of data, but evidently nobody interpreted the findings.

Had the engineer plotted the value of maximum settlement on his contour maps as a function of time, as was done later from his data, he would have seen a fairly constant increase with time up to about two years before the sinkhole occurred, after which a notable acceleration developed. No more complex interpretation than such a plot would have told him that the settlement was rapidly getting out of control and that a sinkhole was imminent. It probably could not have been prevented at that stage, but at least the properties within the center of activity could have been salvaged.

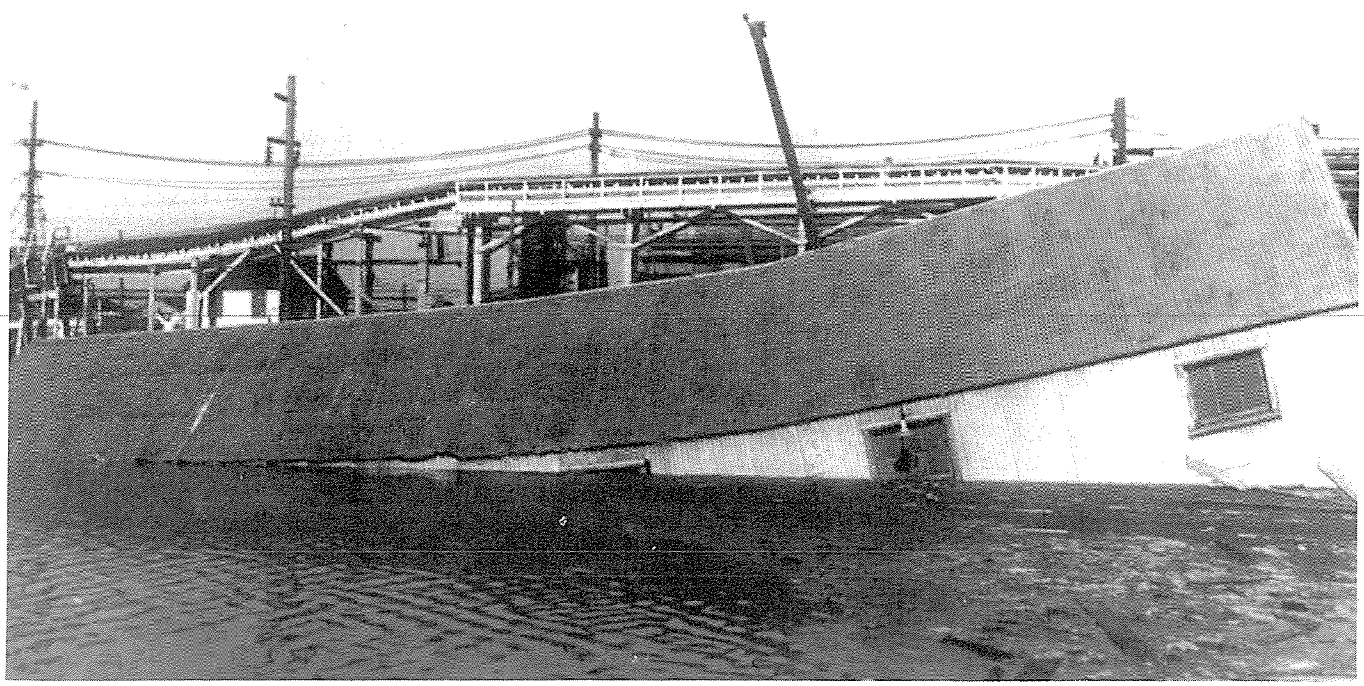
The sinkhole made, not surprisingly, a considerable impression on companies producing salt from brine, and for a few years salt mechanics competed with soil mechanics for my time in the large areas of Canada and the United States underlain by the Salina formation.

Episode 5 - The Red Tail Lights

In 1946 Terzaghi prepared a report on the stability of the dikes at Beauharnois. The dikes had been constructed largely by depositing dredged material on flat slopes, except for two small rolled-fill earth dams that connected the dikes to the power house. In his report Terzaghi expressed some surprise that the earth dams, with slopes of 3H:1V and heights as great as 75 ft. appeared to be perfectly sound and satisfactory, "even though the physical properties of the fill material and the degree of compaction did not satisfy even the customary requirements for highway fills with a height of more than 10 feet." Four years later, when the power house was extended, one of the dikes had to be removed. Terzaghi recognized the opportunity to examine the in-situ properties of the material.

In those days Terzaghi held an appointment as lecturer and research consultant at the University of Illinois. His appointment carried with it the resources to carry out small projects that interested him. He suggested that we might undertake a field investigation of the unusually well-behaved dam at the time of its removal. Accordingly, on September 5, 1950, Herb Ireland, Tom Fry, and I set out in a University car for Beauharnois with our portable digging and testing equipment.

At the site we found Professor A. H. S. Adams of the Civil Engineering Department of the University of Toronto.



4. Subsidence and flooding at Windsor Sinkhole.

He was doing field control work for the power company and was much interested in our assignment. When we told him that we also intended to take a brief excursion to see the old flow slide at St. Thuribe on the Riviere Blanche as well as some of the old parish churches that were reported to have suffered extensive settlements on deep clay foundations, he invited himself to come along. We were a little dubious, partly because our University car was rather tight for space, and partly because he seemed to be extremely voluble as indeed he proved to be.

A block diagram illustrating the St. Thuribe slide and an ancient predecessor had appeared in the little book by C. H. S. Sharpe, "Landslides and Related Phenomena." Terzaghi included the diagram in the first edition of "Soil Mechanics and Engineering Practice," but the explanation of the slide was quite tentative. We were keen to get samples of the material and determine its properties, particularly its sensitivity and mineralogy.

Finding the slide turned out not to be difficult; the topography looked just as it should have according to Sharpe's diagram. We promptly parked the car alongside the road, got out our augers and sampler, and started drilling a hole at the base of the escarpment.

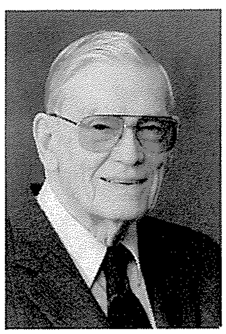
Professor Adams did not seem particularly interested in handling the rods or turning the auger, so he stood watching. Shortly, the farmer in whose field we were digging the hole appeared, in not too pleasant a frame of mind, to find out what we were doing on his property. I must admit it had never occurred to us that we were trespassing on someone's farm. We quickly realized that we were in a most disadvantageous position, particularly since the farmer was releasing a torrent of French that none of us understood. It was here that Professor Adams stepped into the gap. He talked to the farmer in French with a strong Scottish accent, explained to the farmer (as we found out later) the great scientific interest in his property, evidently inquired about the farmer's wife and children, and soon had the farmer helping us with our manual labor. We showed him how we conducted our unconfined compression tests, and how the material, when remolded, ran out between our fingers. The farmer was quite intrigued with the apparent uniqueness and importance of his property, and Professor Adams took on a new dimension among us intruders.

As we went on to visit churches at St. Casimir, St. Tite, and Nicolet, Professor Adams was at once our press agent and interpreter. Parish priests were only too happy to tell us the history of the problems with their structures, to volunteer dates of important events, and to recall some of the catastrophic consequences of both slides and settlements. It was a trip not to be forgotten by any of us.

When we returned and finished our work at Beauharnois, Professor Adams asked us if we could drive him home to Toronto and join him and his wife for evening tea. He shortened the trip with unceasing anecdotes and, when it became dark, undertook to pilot us through the highways and into the streets of Toronto. As a pilot, he left something to be desired, because his stories tended to preoccupy him to the extent that he would forget to give us directions. At the last minute, he would realize we should be making a turn and would exclaim, "follow the car with the red tail lights." As the driver, I found it something of a problem to decide which red tail lights were the ones to follow, but we did eventually arrive at his home for a pleasant evening. For many years within our group at Illinois, the standard way to get a discussion on track was to suggest "follow the car with the red tail lights."

Epilogue

It is no secret in the geotechnical profession that Canada, particularly British Columbia, was Karl Terzaghi's favorite place to work: the compelling beauty of the land and the shear audacity of the engineering problems were irresistible attractions. For me, the engineering challenges from Bennett and Mica Dams to Churchill Falls and James Bay were no less challenging, even though my part was advisory rather than dominant as was Terzaghi's. Yet, I have had the satisfaction, that Terzaghi could not know, of returning again and again to the land of my origin. It has been a rewarding experience.



RALPH B. PECK was born in Winnipeg, Manitoba, in 1912. He grew up in Denver, where his father was engineer of structures for the Denver and Rio Grande Western Railroad. He received the degrees of civil engineer and doctor of civil engineering at Rensselaer Polytechnic Institute in 1934 and 1937 with the intention of becoming a structural engineer. But after eight months as a structural detailer with the American Bridge Company, he attended the soils mechanics classes of Professor Arthur Casagrande at Harvard until January 1939. At this time Dr. Karl Terzaghi became a consultant to the city of Chicago for the design and construction of the initial system of Chicago subways and Peck became his representative on the job. In December 1942 Peck joined the Civil Engineering Department of the University of Illinois at Urbana, from which he retired in June, 1974.

Dr. Peck has been a consultant on foundations for buildings, ore docks and other heavily loaded structures on tunnels and open cuts for subway systems, and on dams including Mica Dam, Bennett Dam, and the Churchill Falls and James Bay hydroelectric projects, in Canada. He has continued to consult from his home in Albuquerque, New Mexico.

Dr. Peck has co-authored over 200 technical papers, but is best known for the textbook, **Soil Mechanics in Engineering Practice**, co-authored with Karl Terzaghi in 1948 and now in its third edition. Dr. Peck served as president of the International Society for Soil Mechanics and Foundation Engineering from 1969-1973. In 1973 he received the U.S. National Medal of Science from President Ford.

Canadian Geotechnical Society
A Brief History

A.G. (Tony) Stermac

The Canadian Geotechnical Society is one of the Canadian Learned Societies. Its mandate and purpose was and remains "to provide for its members opportunities for updating and upgrading their technical knowledge and skills and to present results of their research and other technical achievements." The Society is an excellent, varied and broadly based forum for lifelong continuing education for its members.

The Canadian Geotechnical Society was formally organized as a Constituent Society of The Engineering Institute of Canada in 1972. The origins of the Society go back to 1946 when the National Research Council of Canada established the Associate Committee on Soil and Snow Mechanics (later to be called the Associate Committee on Geotechnical Research), with Dr. Robert Legget as Chairman. Dr. Legget, at that time, was a Professor of Civil Engineering at the University of Toronto and was giving soil mechanics instruction. In 1947, Dr. Karl Terzaghi, President of the International Society for Soil Mechanics and Foundation Engineering (ISSMFE), acting on Resolution No. 3 adopted at the First International Conference of ISSMFE in 1936 in Cambridge, Massachusetts, called upon Dr. Legget to organize a Canadian Section of ISSMFE and to be the Canadian delegate to the International Executive Meeting which would be held in Rotterdam in 1948, at the time of the Second (first post-war) ISSMFE Conference.

Dr. Legget, in his capacity as Chairman of the Associate Committee, convened a conference in Ottawa on April 28-29, 1947 of all those persons known to be interested in soil mechanics in Canada. Some 40 individuals attended this meeting, which was in reality the first Canadian Geotechnical Conference, and marked the beginning of organized geotechnical activity in Canada. The Conference established a Subcommittee on Soil Mechanics comprising a chairman and six regional representatives. This small group acted as the Canadian National Committee at the Second International ISSMFE Conference in Rotterdam. The individual members established local groups in larger centres that, in most cases evolved into local sections or groups of the Canadian Geotechnical Society. The original establishment of local groups laid the foundation for organized geotechnical activities all across the country, Activity grew steadily during the 1950s, with a conference held annually. By 1960, the Engineering Institute of Canada began organizing an Engineering Geology Division, which worked closely with the Associate Committee, and in 1962 assumed the organization of the annual Geotechnical Conference. From 1972, though, the responsibility for the organization of annual conferences rested exclusively with the Society. In 1997 the Society will organize its 50th Jubilee Conference in Ottawa, where it all began 50 years ago. To the best of our knowledge that is the longest continuous organization of Geotechnical Conferences in the world! It is also interesting to note that Society member Gordon McRostie from Ottawa has attended all Canadian Geotechnical conferences except one when he unwisely(!) decided to attend a conference in Mexico instead of in Canada. He has attended, so far, 48!

The Montreal Conference was in all respects very successful and was considered by many to be one of the best organized conferences of its kind, demonstrating to the world that Canadian geotechnique has come of age.

The main Society activities, though, take place at the grass root level, in the local organizations, sections and groups. For years and years eminent speakers present more than 100 technical lectures annually in local organizations across the country. In addition, since 1965, the Society has organized two Cross Canada Lecture Tours annually. Invited lecturers tour the country and lecture in 8 to 10 centres in a two-week period. So far there have been a total of 58 speakers, 28 prominent Canadian experts and 30 outstanding foreign specialists from all over the world.

In 1963, a group of enthusiasts in the Southern Ontario Section, under the leadership of Vic Milligan who edited the Journal for the first 5 years, began the publication of the *Canadian*

Geotechnical Journal which, although initially published independently, in 1970 it became one of the scientific Journals published by the National Research Council.

In 1965, Canada acted as host for the Sixth International Conference of the ISSMFE, held in Montreal. Again, the Conference was organized by a Committee established by the Associate Committee and involved many individuals. The Montreal Conference was in all respects very successful and was considered by many to be one of the best organized conferences of its kind, demonstrating to the world that Canadian geotechnique has come of age.

The Canadian Geotechnical community matured rapidly following the 1965 Montreal Conference. There were continuing efforts for establishing a self-governing Geotechnical Society, which was finally achieved in 1972 with Geoffrey G. Meyerhof as its first President. Since then the Society has had the following succeeding Presidents: T.C, Kenney, D.H. Shields, J.I. Clark, J.I. Adams, A.G. Stermac, D.W. Devenny, M. Bozozuk, N.R. Morgenstern, F. Tavenas, J.L. Seychuk, J.M. Laing, and J.P. Graham. In 1985 the Canadian Geotechnical Society was federally incorporated as a financially independent and self-governing learned society. The following table lists the membership numbers of the Canadian Section at five-year intervals and indicates the steady growth of interest in geotechnical activities in Canada, since the first conference in 1947.

Membership: Canadian Section

1950	50
1955	130
1960	206
1965	313
1970	560
1975	583
1980	920
1985	1200

The Society presently publishes its newsletter as "CGS News" in the quarterly magazine *Geotechnical News*. The newsletter has its origins in 1963 when it was the medium to keep members of the Canadian Section of the ISSMFE informed of the planning for the 1965 International ISSMFE Conference in Montreal. The newsletter was issued on a random basis. Following the Conference the mimeographed newsletter was published three or four times a year. When the Society was established in 1972, the newsletter was issued on a more regular basis with W.J. Eden from the National Research Council as editor. In 1976, through the efforts of John Gadsby of BiTech Publishers in Vancouver, a regular quarterly publication called *CGS News* began. In 1983 the US National Committee of the ISSMFE joined and the production of *Geotechnical News* magazine started. Both *CGS News* and *USNS News* became part of the Geotechnical News magazine. In 1984 the Mexican National Society was invited to become part of the magazine to make it a truly North American communications medium. Unfortunately this has not yet materialized.

The Society regularly publishes proceedings of its annual and other conferences. It also publishes the highly regarded *Canadian Foundation Engineering Manual*. In 1993 the 3rd Edition was published. The French version of the 3rd Edition appeared in 1995.

Since its formation the Canadian Geotechnical Society has organized and co-sponsored several specialty conferences in addition to the regular annual Geotechnical Conference. Examples are the Conferences on Marine Geotechnical Engineering held in 1979, 1982, 1986 and 1993, and the Canadian Permafrost Conferences. There have been seminars arranged on Geosynthetics and Urban Slope Stability. In the field of international activities the Canadian Geotechnical Society has acted as host for the VII Pan American Conference on Soil Mechanics and Foundation Engineering held in Vancouver in 1983, the IV International Symposium on Landslides in Toronto in 1984 and the International Symposium on Environmental Geotechnics in 1994 held in Edmonton.

In 1990 the Society decided as of 1991 to organize annually a Specialty Spring Conference. Such conferences were organized in 1991 in Montreal, in 1992 in Vancouver, and in 1993 in St. John's. The 1994 Specialty Conference was the Edmonton Symposium. In 1996 the Spring event was the North American Rock Mechanics Symposium in Montreal

The Spring Specialty Conferences can be events co-sponsored with other national or international organizations.

Starting with one general division composed mainly of soil mechanics specialists, the Society soon recognized the need to accommodate other disciplines in the geotechnical field. Therefore four divisions were formed starting in the 1970s: Engineering Geology, Rock Mechanics, Cold Region Geotechnology, and Soil Mechanics and Foundations which remains the largest division.

The concern about the protection and late 80s and early 90s assumed centre stage. Of the three elements, soil/rock, water and air, the first two are within the geo domain. In order to respond to, and effectively deal with the identified geo-environmental issues, needs and problems the Society has organized the Geoenvironmental Division, its fifth.

Geotextiles or Geosynthetics, although relatively new materials, have a most important place in activities of geotechnical professionals, especially in the area of environment protection. The Society had for many years an extremely active Geosynthetics Committee. In order to provide Geosynthetics a well-deserved high national profile the Society has organized, in 1993, the Geosynthetics Division, its sixth. In 1995 the Society welcomed as members an appreciable number of hydrogeologists who created the seventh technical Division the Hydrogeology Division.

From the above it is obvious that the Canadian Geotechnical Society has indeed become, in the 90s, the home of the majority of Canadian geo professionals active in the civil engineering and other related fields, thus enabling closer co-operation and cross-fertilization between these professionals. All of them have equal rights and responsibilities in the Society, and the Society speaks with one voice for all of them both nationally and internationally.

The Canadian Geotechnical Society has so far demonstrated that it is above all a most useful forum for continuing education of its members, that it is progressive, flexible and adaptable. As the environment changed, the Society changed. Whatever changes took place they were introduced with only one objective in mind. This objective is, and we trust will always remain:

"How to better serve the needs of Society members, the profession and the country."

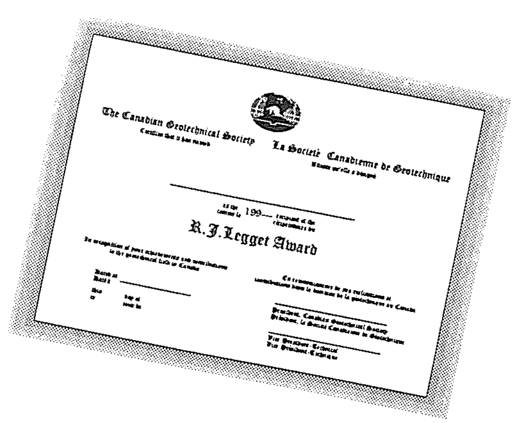
Note: A large part of the above text was excerpted from the article "Canadian Geotechnical Society" by W.J. Eden, published in Geotechnical News, June, 1985.

The R.F. Legget Award

A.G. (Tony) Stermac

How did the Legget Award come about?

The decision was reached to create a Society award to be presented annually at the Society Conference to one most-deserving selected Society member. Dr. Legget was always considered as the "father of soil mechanics", later called geotechnique, in Canada. Not only was he largely responsible for the acceptance and recognition of soil mechanics as a valid and indispensable engineering discipline, he was also in fact the founder of what is today the Canadian Geotechnical Society. What better way to express the Society's and the Canadian geotechnical community's gratitude and indebtedness to the "founder" than to have the award named after him. And so the award was named "The R.F. Legget Award."



The creation of the Legget Award in 1969 was especially appropriate because that year Dr. Legget retired form the National Research Council.

The first R.F. Legget Award was presented in 1970. It was awarded posthumously to Robert Peterson, the prominent and pioneering Canadian geotechnical engineer whose career was intimately connected with PFRA and the work that this agency did in Western Canada.

The Society has subsequently created other awards,however the R.F. Legget Award is and remains the most senior, most prestigious and most coveted Society award.

The criteria for the R.F. Legget Award are as follows:

The Award is given to an individual who has made the most significant personal contributions to:

- the development of an understanding in Canada of the interrelationship of civil engineering and engineering geology through publications, research or professional society activities, or
- development of theoretical and applied techniques to problems concerning the geotechnical field in Canada, or
- the supervision of geotechnical or civil engineering projects of importance to the Canadian economy, or
- the stimulation of geotechnical activities in Canada through the encouragement of co-workers, associates and students, or
- any other achievements of permanent significance in the field of geotechnical engineering in Canada.

The Selection Committee for the R.F. Legget Award is constituted as follows:

Chairperson

- Incumbent CGS President

Members

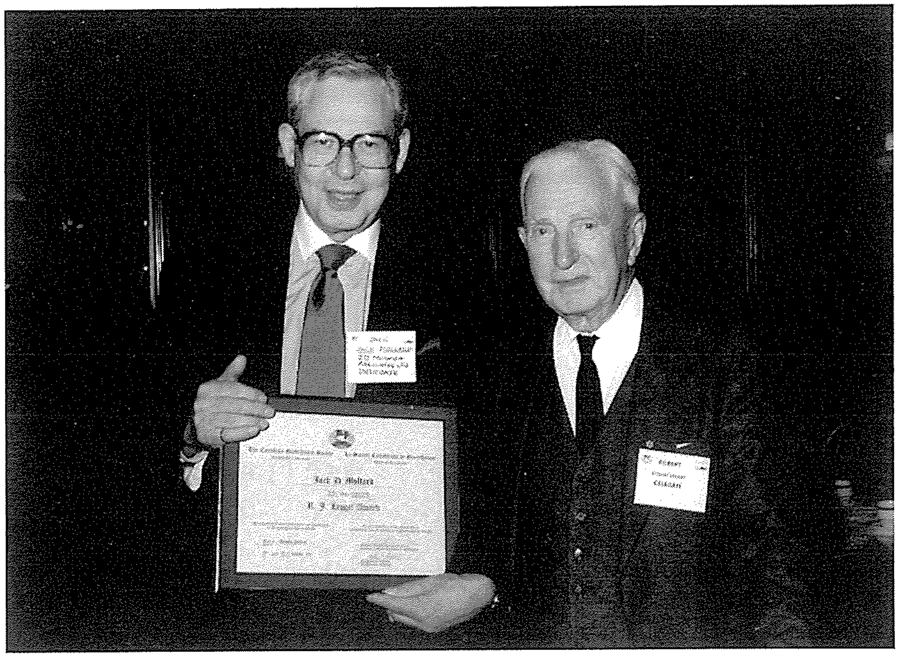
- Incumbent Vice President-Technical
- Incumbent Editor, *Canadian Geotechnical Journal*
- Incumbent Chairperson, CGS Geotechnical Research Board

To date 27 Society members have been recipients of the Legget Award.

The Award is a bilingual framed certificate and is presented to the recipient by the Society President at a special ceremony during the annual conference. While Dr. Legget was alive he was asked to present the Award personally. Dr. Legget made it a point to attend the annual conference and has therefore missed very few.

There is now a Society member who introduces the current Award winner and the winner is provided the opportunity to respond and express thanks for the Award. However, this was not always the case. The Award ceremony was not always a special separate occasion at the Conference. The procedure and the format of the presentation evolved through the years. A funny thing happened in 1972 during the Conference in Ottawa. When Dr. Legget stepped forward to present the award to the late Norman McLeod, the certificate was missing, nowhere to be found. Dr. Legget did not loose his cool, reached into his wallet and presented to Norman his calling card, saying "This is the raincheque for the Certificate." This little and amusing incident best symbolizes the Society's development and maturing, the "where we were and how far we have come."

The R.F. Legget Award presentation ceremony has certainly been and remains one of the highlights of the Annual Society Conference because we celebrate and award the best and most deserving among us.

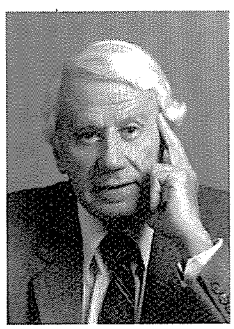


Jack D. Mollard receives the R.F.Legget award from Dr. Legget, 1992

Recipients of the Legget Award

These individuals are:

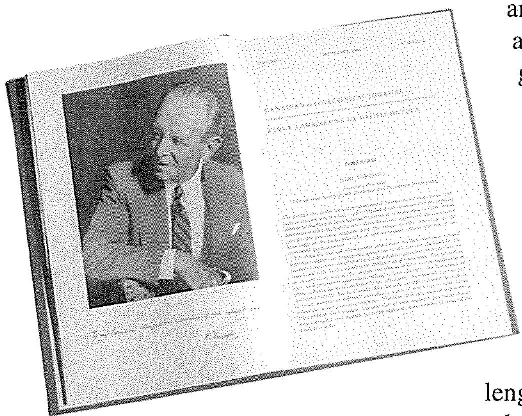
1970 Robert Peterson
1971 Robert M. Hardy
1972 Norman W. McLeod
1973 Victor Milligan
1974 G. Geoffrey Meyerhof
1975 Carl B. Crawford
1976 Anthony G. Stermac
1977 Pierre LaRochelle
1978 Donald H. MacDonald
1979 Norbert R. Morgenstern
1980 Roger Brown
1981 Branko Ladanyi
1982 Donald J. Bazett
1983 Jack I. Clark
1984 Laval Samson
1985 John I. Adams
1986 M.A.J. (Fred) Matich
1987 C.F. (Charlie) Ripley
1988 W.A. (Bill) Trow
1989 K.Y. Lo
1990 Earle J. Klohn
1991 Robert M. Quigley
1992 Jack D. Mollard
1993 Raymond N. Yong
1994 Mike Bozozuk
1995 François Tavenas
1996 John L. Seychuk



A.G. (TONY) STERMAC was born in Zagreb, Croatia and graduated in civil engineering from the University of Zagreb in 1949. In 1958 he obtained the Doiploma of Imperial College, University of London, England.
Stermac was an assistant professor, then worked with a consulting company in Zagreb.
When he came to Canada in 1960, he started with the Ontario Department of Highways (now Ministry of Transportation) retiring in 1987 as Director of the Transportation Technology and Energy Branch.
Mr. Stermac has a long record of service to the Canadian Geotechnical Society, being associate editor, then editor of the *Canadian Geotechnical Journal* from 1963-74, president 1983-84, and from 1987 as Director General of the Society. He has won society awards and in 1996 was recipient of the John B. Sterling Medal of the Engineering Institute of Canada.

Twenty-five Years of the Canadian Geotechnical Journal

Donald J. Bazett



Publication is as vital to a profession as advertising is to a trade although there are major differences in approach. In professional publication, discoveries are shared and knowledge advances on the experience of all; profit arises from the common pool of knowledge. In the commercial world advertising is used to proclaim a product or service in contrast to its competitors; research is guarded and profit arises from individual endeavour rather than shared advances in knowledge. As geotechnical engineers we have now been blessed for more than twenty-five years (thirty-three years, in fact) with publication of the *Canadian Geotechnical Journal* (CGJ). This publication represents a considerable effort by the Canadian Geotechnical community, a commitment by the Canadian government through the National Research Council (NRC), and it also represents an awesome contribution by the volunteer editors, associate editors, and reviewers.

Questions that arise in my mind from such efforts are: "Why do we do it?" and "What purpose does it serve?" Answers can perhaps be found in the history of the journal.

The Fourteenth Canadian Soil Mechanics Conference was held at Niagara Falls in October 1960. At this conference major papers on till, marine clay, and lacustrine clay were presented and the high standards of Canadian geotechnical engineering became apparent. Previous conferences had been considered as research conferences for the exchange of information and the stimulation of the research aspects of soil mechanics. The NRC in technical memoranda recorded the transactions of these conferences. The appearance of relatively lengthy articles disturbed the system and the Division of Building Research pointed out that they had no mandate to enter the publishing business and agreed only to publish abstracts or reduced versions of the papers. It was apparent that, whilst the content of the conferences would become more exacting, there would be no easy method of publication available in Canada.

Following the conference in a lounge at the top of the Brock Hotel and in the euphoria following several strenuous days, Vic Milligan, David Townsend and I as chairmen of the Toronto Soils Group, the Soil Mechanics Subcommittee of Associate Committee of Geotechnical Research (ACGR), and the local conference committee, respectively, decided to invent our own journal. We might become the Toronto Society of Civil Engineering (cf. the well-known Boston Society), we might become a group dedicated to publish conference proceedings or we might even become a national journal. To be practical we agreed to explore the ideas of publication in detail.

An exploratory meeting was subsequently held in November, 1960 for which I can find only pencilled notes; those present were: D.J. Bazett, H.Q. Golder, L.G. Soderman, F.A. Delory, V. Milligan, A.G. Stermac, A. Gass, A. Prior

Little was decided at this meeting except that those present would correspond with colleagues in all parts of the country stating our purpose and asking three questions: (1) would they be interested in a published journal?, (2) would they subscribe to such a journal?, and (3) would they publish in such a journal? I remember one side issue: would the Canadian community resent the journal as a move by an aggressive Toronto? The answer was, "Who is from Toronto?" Whilst we were living there, the nearest point of origin of those present was Minaki, Ontario at the Manitoba boundary from which Larry Soderman came. It was a diverse group and was typical of the many groups and committees I have known in Canadian engineering. It was not parochial, it was not regional in its approach to publication, and it was not narrow-minded in its interests.

A following meeting was held in January, 1961, to assess the response to the initial inquiries and to decide how to proceed. The minutes of this meeting are attached as Appendix I. With an expected initial circulation of 100, the Canadian Geotechnical Journal (CGJ) had acquired a name and had begun to find its way into the world.

Hugh Golder as one of the original committee had been involved in the beginnings of *Geotechnique* and his help at this stage was inspirational. Golder Associates from an early date took a leading role in development, and the early success of the journal was largely due to their efforts.

Robert Legget at this time was involved in launching the *Journal of Earth Sciences* as one of the NRC Journals of Research and his initial reaction to the CGJ was antagonistic. He did not believe the journal to be needed or wanted. The journal, however, took on a life of its own and a provisional committee was formed and a national policy came into being. Subsequently, Dr. Leg-

APPENDIX II - Figure 1

■ = Editor □ = Original Editorial Board ○ = Original Associate Editor ● = Associate Editor

Editors & Associate Editors	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Year		1965					1970					1975					1980					1985			
MILLIGAN, V.	■	■	■	■	■	●																			
DeLORY, F.A.	○	○	○	○	○	■	■																		
STERMAC, A.G.	○	○	□	□	□	●	●	■	■	■	■														
BAZETT, D.J.	□	□	○	○	○	●	●	●	●	●	●	■	■	■	■	■	■								
QUIGLEY, R.M.												●	●	●	●	●		■	■	■	■				
GRAHAM, J.																	●	●	●	●	●	■	■	■	■
BROWN, J.D.												●	●	●											
CLARK, J.I.											●	●	●	●	●	●	●	●	●	●	●	●	●	●	
COATES, D.F.								●	●	●	●														
CRAWFORD, C.B.	□	□	□	□	□	□																			
GOLD, L.W.	○	○	○	○	○		●	●	●	●	●	●	●	●	●	●	●	●							
HARDY, R.M.								●	●	●															
LaROCHELLE, P.	□	□	□	□	□	●	●																		
McCAMMON, N.R												●	●	●	●	●	●								
SAMSON, L.	○	○	○	○	○	●	●	●	●	●	●	●	●	●	●	●									
SEYCHUK, J.L.												●	●	●	●	●	●	●							
TAVENAS, F.								●	●	●	●	●	●	●	●	●	●	●							
TOWNSEND, D.L.	○	○	○	○	○		●	●	●	●	●	●	●												
CHAGNON, J.Y.															●	●	●	●	●						
MORGAN, G.C.														●											
HAMILTON, J.J.															●	●									
BURWASH, A.																●	●								
KENNEY, T.C.																	●	●	●						
TOURNIER, J-P.																	●	●							
SLY, P.G.																		●	●	●					
YONG, R.N.																		●	●	●	●	●	●	●	●
NIXON, J.F.																		●	●	●	●	●	●	●	
McCREATH, D.R.																		●	●	●	●	●	●	●	
EISENSTEIN, Z.																			●	●	●				
GARNEAU, R.																			●	●	●				
READES, D.W.																			●	●					
ROGGENSACK, W.																			●	●					
BOZOZUK, M.																			●	●	●	●	●		
MITCHELL, R.J.																				●	●	●	●		
LEFEBVRE, G.																				●	●	●	●	●	●
ROWE, R.K.																				●	●	●	●	●	●
CHATTERJI, P.K.																				●	●	●	●		
LAFLEUR, J.																					●	●	●	●	●
LEE, C.F.																						●	●	●	●
MITCHELL, D.E.																						●	●	●	
BAIKIE, L.D.																						●	●	●	●
CHERRY, J.																						●	●	●	●
CROOKS, J.H.A.																								●	●
FREDLUND, D.G.																								●	●
DASCAL, O.																								●	●
KAISER, P.K.																								●	●
McROBERTS, E.																								●	●

Appendix II, Figure 1. Editors and Editorial Boards

get changed his views to become a major supporter of the journal (such change in my experience is rare in this wicked world and is always a mark of greatness). He obtained the support of the ACGR (NRC) and the Engineering Institute of Canada so that initial publication could claim the support of both groups.

An editorial board with Vic Milligan as Editor including a number of associate editors followed and Pierre LaRochelle as one of the board brought us to face the French fact and our bilingual responsibilities. The *Canadian Geotechnical Journal* became *also Revue Canadienne de Gèotechnique*, added an invitation for papers in French and French abstracts to all articles. A start was made on paper selection and the format of the proposed journal began to take shape with the help of experts at the University of Toronto Press.

Fundamental question of policy soon arose. For example, Why have a journal?; *Gèotechnique* served the international community, *The Engineering Journal* served Canadian engineering needs. The ASTM and ASCE were available for technical articles. Would the Canadian journal compete with *Gèotechnique*? and should it? What papers would be accepted? Was it to be essentially concerned with engineering, geology, exploration, or testing? How strong a theoretical base should it have?

These problems were addressed by Karl Terzaghi in the opening issue where he said,

"The publication of the *Canadian Geotechnical Journal* is the most recent and most important step in what I called 'Regional Developments' in my opening address to the Second International Conference in Rotterdam in 1948. These developments are the link between theoretical and applied soil mechanics and provide the practising engineer with the means to take advantage of our knowledge of the basic principles of soil mechanics without the risk of un-warranted generalization.

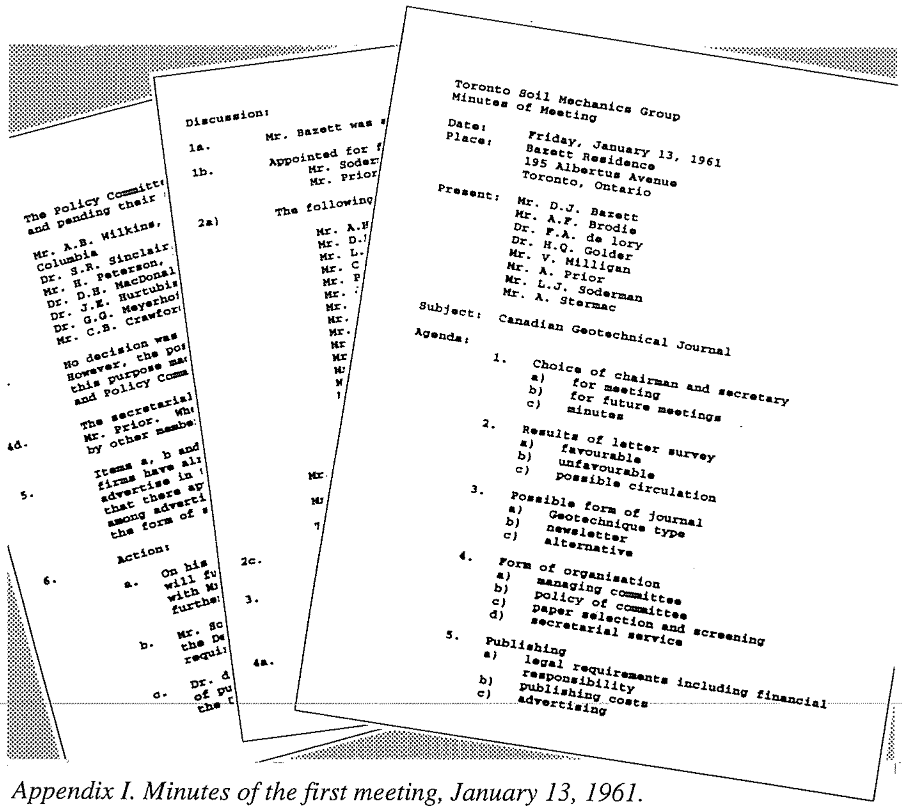
"The need for regional development arises from the fact that most natural soils have significant engineering properties which are not disclosed by the results of the conventional procedures of subsoil exploration, because they are associated with local geological or climatological conditions. The properties of varved clays and of clay shales, the effects of time on the brittleness of clay, and permafrost phenomena belong to this category. Our knowledge of these subjects is based exclusively on adequately documented case or performance records. Yet in Canada these records are still scattered throughout a great number of different periodicals, some of which never come to the attention of the practising engineer. Therefore this new journal will serve a vital need of the Canadian engineer and of those engineers practising abroad who encounter soil deposits with the regional

APPENDIX II - Figure 2

■ = Editor · □ = Original Editorial Board ○ = Original Associate Editor ● = Associate Editor

Editors & Associate Editors	Vol. 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Year		1965					1970					1975					1980					1985			
BARACOS, A.	○	○	○	○																					
GRAVENOR, C.P.	○	○	○	○	○																				
HARWOOD, T.	○	○	○	○	○																				
HURTUBISE, J.E.	○	○	○	○	○																				
LARDNER, W.E.	○	○	○	○	○																				
MacDONALD, D.	○	○	○	○	○																				
MATTHEWS, W.H.	○	○	○	○	○																				
MEYERHOF, G.G.	○	○	○	○	○																				
PECKOVER, F.L.	○	○	○	○	○																				
PETERSON, R.	○	○	○	○	○																				
POUNDER, E.R.	○																								
RADFORTH, N.W.	○	○	○	○	○																				
RIPLEY, C.F.	○	○	○	○	○																				
SCOTT, J.S.	○	○	○	○	○																				
SINCLAIR, S.R.	○																								
SODERMAN, L.G.	○	○	○	○	○																				
TROW, W.A.		○	○	○	○																				
WARKENTIN, B.P.	○	○	○																						

Appendix II, Figure 2. Editors and Editorial Boards


Toronto Soil Mechanics Group
Minutes of Meeting

Date: Friday, January 13, 1961
Place: Barett Residence
195 Albertus Avenue
Toronto, Ontario

Present: Mr. D.J. Barett
Mr. A.F. Brodie
Dr. F.A. de lory
Dr. H.Q. Golder
Mr. V. Milligan
Mr. A. Prior
Mr. L.J. Soderman
Mr. A. Stermac

Subject: Canadian Geotechnical Journal

Agenda:

1. Choice of chairman and secretary
   a) for meeting
   b) for future meetings
   c) minutes
2. Results of letter survey
   a) favourable
   b) unfavourable
   c) possible circulation
3. Possible form of journal
   a) Geotechnique type
   b) newsletter
   c) alternative
4. Form of organisation
   a) managing committee
   b) policy of committee
   c) paper selection and screening
   d) secretarial service
5. Publishing
   a) legal requirements including financial responsibility
   b) publishing costs
   c) advertising

Appendix I. Minutes of the first meeting, January 13, 1961.

characteristics of some of the Canadian soils."

These comments were amplified by Dr. Legget who in an introduction to the journal said as follows:

"The Journal is intended to provide a medium for the publication of papers in the applied geotechnical field. It is anticipated that most of the papers presented will deal with soil mechanics. In keeping, however, with the liaison with allied fields that has always characterized Canadian soil mechanics work, papers dealing with associated subjects such as engineering geology, pedology, muskeg, hydrology, and the mechanics of snow and ice will always be welcomed by the Editorial Board.

"Although the *Journal* is intended to provide an outlet for Canadian papers, suitable contributions from other countries will be accepted. It is therefore appropriate to observe that this publication will be supplementary to the international journal *Gèotechnique*, the Editorial Board of which has kindly sent their good wishes. Correspondingly, the President of the International Society, Professor Arthur Casagrande of Harvard University, has also sent his commendation."

It is also instructive to note the journals own definition of itself:

"The *Canadian Geotechnical Journal* publishes papers, in English or French, covering the general field of soil engineering together with papers in the related disciplines of Geology, Soil Science, and Snow and Ice Mechanics as they relate to civil engineering."

The 25th volume had altered this slightly to read:

"The *Canadian Geotechnical Journal (Can. Geotech. J.)* publishes papers, in English or French, in the broad area known as geotechnical engineering. Papers are welcomed on traditional topics such as foundations, excavations, soil properties, dams, and slopes. Authors are encouraged to submit papers on newer topics like geohydrology, rock engineering, natural resource development, waste management, geosynthetics, geochemistry, frozen soil, ice and snow, geostatistics, and offshore geotechnical engineering, particularly if they are directed to the needs of practising engineers."

Currently this definition has become:

"The *Canadian Geotechnical Journal (Can. Geotech. J.)* publishes papers, in English or French, in the broad fields of geotechnical and geoenvironmental applied sciences. Papers are welcomed on traditional topics in the areas of earth (soil and rock) mechanics, foundation engineering, earth structures, and geological engineering. Authors are encouraged to submit papers dealing with developments and applications in contaminant hydrogeology, contaminant detection and mitigation, geochemistry, geosynthetics, geostatistics, offshore engineering, northern engineering, and other similar areas. Case records and papers of interest to geotechnical practitioners are particularly encouraged."

The problems of content remain vital to the success of the *Journal*. Who is it published for: the authors? the readers? academics? practicing engineers? What subjects should it emphasize: engineering? pure science? theoretical studies? case records? field work? or laboratory work?

In the years when I had some responsibility for content, priority was given to case records of engineering projects of primary interest to practicing engineers with special attention to the authors of papers presented at annual conferences of the Canadian geotechnical community. The best of such papers were believed to be those describing a project including analysis, testing, design and performance. The outstanding papers included innovative concepts.

Questions of content are the continuing responsibility of the editor with the assistance of his board. Their judgements will also be influenced by the reviewers representing the greater community as they accept manuscripts on a paper by paper basis.

With consensus on such issues, a final meeting was held with Drs. Legget and Golder and the editorial board in early 1963. The journal was finally launched and publication of Vol 1 No 1 was prepared for September, 1963.

Drs. Legget and Golder volunteered to act as personal guarantors of payment to the University of Toronto Press in the event that the fledgling journal could not meet its printing bill. It should be pointed out that revenues to pay printing bills were to be derived from advertising. The responsibility for getting such advertising was splendidly discharged by Bill Lardner.

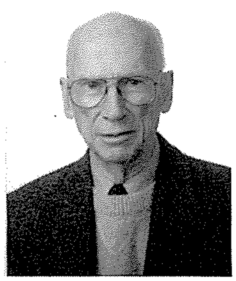
Initially, the work of publishing the journal was largely those of Vic Milligan as editor, and Golder Associates at their office over a piano shop on Bloor Street in Toronto. I note the location to emphasize the difference from the corporate vastness of Golder Associates today and the struggling company that devoted its energy to a young, vulnerable, and non-profitable professional enterprise.

The first five volumes (1964-68) were published with Vic Milligan as editor and during this time he negotiated with the NRC to include the CGS as one of their Journals of Research. These volumes were published without outside financial aid, but with much support from the associate editors and the local geotechnical society. With increasing acceptance of the journal in Canada and internationally, Dr. Legget was able to persuade the NRC to recognize its worth and include it as one of their scholarly Journals of Research. It was then appropriate for the original editor, Vic Milligan, to step aside and the sixth volume was published by the NRC with Fred Delory as editor but with the format unchanged. After this the format was altered and the NRC has remained the publisher ever since.

F.A. Delory was the editor for the 6th and 7th volumes. A.G. Stermac succeeded him and was the editor for volumes 8 through 11. D.J. Bazett was the editor for volumes 12 through 17, R.M. Quigley for volumes 18 through 21 and J. Graham was the editor for volumes 22 through 25. (Subsequent editors have been J.I. Clark, volumes 26 through 29, R.J. Mitchell, volumes 30 through 33).

A list of all the editors and the editorial boards is included in Appendix II. It can be seen that the list is representative of Canadian geotechnical engineering and has included representatives from all parts of the country.

The journal has already served a need and has joined the world literature in its field. How well it continues to do this depends on its editors and the extent to which they meet the needs of their society. It is important that they assess correctly the needs of their readers. I cannot end, however, with the emphasis only on the importance of the editor and the Editorial Board. Ultimately, the success of the journal is dependent upon its authors. Without good quality papers which include the literate description of work of value, both to Canada and engineering in the world, the journal has no need to survive.



DONALD J. BAZETT received his applied science degree in civil engineering from the University of Toronto in 1949, then he took post-graduate training in soil mechanics at London University, England.

Starting out as a soils engineer with Geo. Wimpey & Co. in the United Kingdom, Bazett then worked for Ontario Hydro from 1955-63 on many projects, finally as Supervising Engineer in their soil mechanics laboratory. From 1963-86 he was with CBA Engineering, Vancouver as vice-president and manager of the Geotechnical Engineering Department. Since 1987 he has been a specialist consultant maintaining his own office.

In a long career, Mr. Bazett has participated in many major projects such as the St. Lawrence Power Project, the Niagara Pumped Storage Reservoir, and the Keenleyside (Arrow) Dam in British Columbia. He has been involved in multidisciplinary water resource projects in Brazil and Belize and has managed similar projects in Nigeria and Tanzania. He has designed or reviewed the foundations for many large bridges in the Vancouver area, including the Knight Street Bridge, Alex Fraser Bridge, Mission Bridge, the proposed Burrard Inlet Crossing, as well as the Northumberland Strait Bridge in the Maritimes.

Mr. Bazett has served on various committees relating to the geotechnical community and has received awards for his work. He was on the editorial board of the *Canadian Geotechnical Journal* for seventeen years, six years as editor.

Geotechnical News

Any celebration of the Canadian Geotechnical Society would be incomplete without mention of *Geotechnical News.*

Now in its fifteenth year of publication, *GN* continues to serve as an informative and reliable communications tool for issues of interest to the geotechnical profession. Fully endorsed by the two major bodies in the field of geotechnical engineering, the CGS and the USNS, *GN* provides an essential forum for the interchange of philosophies, technology and methodology related to the area of geotechnics.

Structured to cater to the many varied disciplines within the profession, *GN* covers topics on environmental geotechnics, centrifuge modelling, and geotechnical instrumentation in each issue. The "Marketplace" section of the magazine provides a showcase for the latest products, and in-depth explanations of new technology are given play in regular articles. *GN* is recognized by advertisers as an effective tool for reaching their target market.

Beginnings

Geotechnical News is intrinsically connected to the CGS, as evidenced by John Gadsby's publisher's note, taken from Volume1, No.1, of the March 1983 issue of *Geotechnical News*:

"In the late 1940's Robert F. Legget, then Director of Building Research of the National Research Council of Canada, initiated the formation of geotechnical groups in various cities across Canada. Under the aegis of the National Research Council of Canada, national conferences were organized, the *Canadian Geotechnical Journal* was launched (1963) and a newsletter was produced to disseminate news across the country.

The Canadian Geotechnical Society was formed in 1972. By 1976, the president of the society, Jack Clark, recommended to the CGS Board of Directors that a newsletter should be developed further to provide a better vehicle for communication with Canadian members. The beginnings of the CGS News were established.

Following the 1979 Canadian Conference, David Townsend commented there was little opportunity for members to pass on geotechnical items of a speculative nature, which did not merit a "Technical Note" - Geospec was born. Advertising support from the suppliers to the geotechnical profession was first solicited in 1980 to help defray the costs of producing this growing magazine. By 1980, the need to continue CGS News was clearly identified by the CGS Directors as an essential service to its members.

At the CGS Directors' meeting in Calgary in 1980, ASCE representative George Sowers (then the ISSMFE Vice President for North America) commented at a social gathering that having developed such a communication link perhaps it could include the USNS news...the seed for *Geotechnical News* was sown".

In March 1983 the first issue of *Geotechnical News*, which had the support of both the Canadian Geotechnical Society and the U.S. National Society (USNS) of the ASCE was published. John Gadsby as its publisher, was well qualified. He not only had an insider's knowledge of the subject matter, but he had had a long association with the *CGS News*, having been both its publisher and the editor of Geospec.

Editorial Structure

BiTech is the publisher of *Geotechnical News* and is responsive to both the US and Canadian Societies, whose appointed editors are responsible for collecting their society news. Editorial duties for the other sections e.g. Geotechnical Instrumentation, Centrifuge Modelling, Environmental Geotechnics, etc. are undertaken by

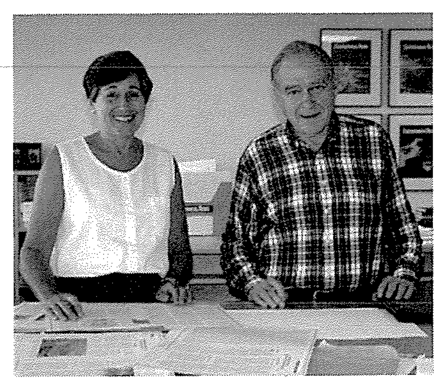
Sandi Braley (left) and Lynn Pugh at BiTech's office.

individuals invited to do so by BiTech. Articles which are sent directly to BiTech are usually included in the Geospec section of the magazine. The general editorial policy is that the quality of the article rests entirely upon the shoulders of the writer. GN does not act as a competitor to technical journals, in that it invites brief articles, perhaps controversial in nature, of current significance yet of professional interest. Each quarter *Geotechnical News* reaches approximately 6000 readers.

Staff

The staff remains small, but efficient and enthusiastic. Lynn Pugh is the managing editor; Sandi Braley, Lynn's right hand, joined BiTech in 1991, and takes care of secretarial and shipping responsibilities; Pat Adams, a freelance graphic designer, is called upon to design the cover and layout of each issue, as she has been doing for the past six years.

Today, *Geotechnical News* has availed itself of the latest in publishing technology. Authors can submit their articles via email, downloading text and graphics directly to Lynn's computer. As methods and technology in engineering have progressed, so has *GN*, but its principal mission, that of providing a service to the Geo-environmental fraternity in North America remains unchanged. Its continued success will depend on "the continued support of enthusiasts, dreamers, doers and advertisers who believe that a channel of communication is required for the North American geotechnical community."



Lynn Pugh and Cyril Leonoff working on this commemorative issue of Geotechnical News.

JOHN W. GADSBY received his M.S. in 1961 from the University of Illinois. He has been a practicing professional engineer for over 40 years. His career has included the investigation, design, construction and operation of resource industry projects, structural design and contracting.

In the past thirty years he has been the project engineer for major resource projects, which require the development of environmentally acceptable solutions, public acceptance, government permits and technical supervision. As the project manager for major mining and water resource projects in Canada and the United States, his skills were retained to interface with engineers, scientists, regulatory agencies and public interest groups.

He pioneered the concept of "Designing for Closure," for mine waste deposits in 1972. This concept consists of planning the operation of the mine, in order that upon closure of the operation, environmental impacts and costs for site rehabilitation are kept to a minimum.

He recently completed a four year study as Project Director for a multi-disciplined team of engineers and scientists responsible for the Environmental Implementation Program on the Zambian Consolidated Copper Mines Ltd. (ZCCM), Corporate Structural Reorganization Project. The project is managed by SRI International and financed by a loan from the World Bank.

In addition to his consulting activities, John Gadsby is frequently invited to be a guest speaker on engineering and the environment at conferences in the United States and Canada. He has been a guest lecturer at the University of British Columbia since 1972. In 1992, he was invited to develop a one week seminar for the Peruvian Mining Association on "Modern Methods of Mine Waste Disposal," and he developed and presented a two week seminar for the Colombian Regulatory agencies on "Mining and the Environment".

Breaking New Ground - Women in Geotechnical Engineering

Anna Lankford Burwash

Introduction

Geotechnical engineering presents very practical challenges. Something needs to be designed or a problem needs to be solved. Safety and affordability are major considerations. High levels of ambiguity are usually a given. Communication skills are very important. The number of women who have chosen to take up these challenges has increased over the last 50 years. However, women still represent a small percentage of the total number of people in geotechnical engineering. Women continue to be in the position of breaking new ground. At first, breaking new ground often meant doing geotechnical work that had never been done by women before. In current geotechnical practice, breaking new ground can be more accurately described as the solution of new problems or pursuit of new activities on behalf of the profession.

This article briefly describes early involvement of women in geotechnical engineering. It identifies from the writer's perspective some of the events and trends in the 1950s and 1960s that helped encourage her to consider the pursuit of post-secondary study and a career in either science or engineering, and may have influenced the choices of other young women at that time. Finally, the article describes some of the activities and contributions of several contemporary women in geotechnical engineering.

Early Involvement of Women

The writer feels quite confident in asserting that women have been involved in geotechnical engineering as long as men have. Many of these women had no formal training in engineering. They provided support and assistance to geotechnical activities in which their husbands were engaged in. For example, Mrs. M. Skempton designed the layout and cover for *Gèotechnique*. The first issue of the journal was published in 1948.

A very notable example of a woman who had Ph.D. level training in geology was Ruth Doggett Terzaghi who worked closely with her husband, Karl Terzaghi. She was described as his "highly competent associate" who even taught some of his classes. (Casagrande 1964)

Mrs. Ellen Louise Mertz, a Danish geologist, was an effective intermediary and networker. In 1950, the position of Head of the Norwegian Geotechnical Institute (NGI) was advertised in the Scandinavian countries. Dr. Laurits Bjerrum was employed by the Swiss Federal Institute of Technology at the time and was likely unaware of this challenging employment opportunity. Mrs. Mertz knew Bjerrum and she knew Olav Folkestad who chaired the selection committee. She told Folkestad that she knew someone who would be a very good candidate for the position. Bjerrum was hired and he had a very distinguished career at NGI until his death in 1973. (Norwegian Geotechnical Institute Staff 1973)

Events and Trends in the 1950s and 1960s

The launch of Sputnik in 1957 increased public awareness of the importance of science and engineering to society. At the time, the writer was a young child who was enrolled in an elementary school in a rural community on the Eastern Shore of Maryland in the United States. Up until this time, teachers in the school had little academic preparation in science and therefore had been hesitant to initiate strong science-based course work in the classroom. This situation quickly changed. The science content increased quickly.

In 1959, the President's Scientific Advisory Committee issued a statement on Education for the Age of Science. The statement stressed the importance of developing the talents of all students to their fullest potential. (Wilson 1992) In the local school, principals asked their teachers to encourage their "good students" to actively consider a career in engineering or science. Without that type of encouragement, very few would have even considered the proposition. Teachers enrolled in science courses in the evenings and participated in special summer programs. Classroom discussions about the activities of the International Geophysical Year (1957-1958) provided additional interest in subterranean investigations. By the time the writer was in senior high school, her small-town school was able to offer a modern physics course that had been developed for secondary schools in cooperation with leading universities including Massachusetts Institute of Technology. These types of developments helped level the playing field so those rural students could compete successfully for admission to engineering and science degree programs at major universities.

Other profound changes came to the writer's small town in the late 1950s and early 1960s as a result of increased national emphasis on research and development in space. In 1958, the creation of the National Aeronautics and Space Administration (NASA) marked the beginning of a civilian space program in the United States. An aeronautical launch facility on nearby Wallops Island in Virginia was the site of studies to support the human space program. As the facility's staff grew in numbers, there was an influx of technicians, engineers and scientists who worked in the NASA Space Program. Their children enrolled in the local schools and university. Students from other parts of the country came to participate in cooperative work terms. In short, high technology arrived on the doorstep of a community that had been largely engaged in agriculture and food processing. It was clear to local students that with the right blend of education and experience, a person could have a challenging career in engineering or science.

In the 1960s, engineering curricula in universities began to stress scientific fundamentals (Grayson 1996). Although the undergraduate degree curriculum varied from university to university, it was often possible for a person who was interested in pursuing a technical career to delay making a decision between engineering or science until the second or third year of study. From the point of view of a woman who had an interest in engineering, this approach represented an opportunity to try engineering without a significant delay in graduation if she decided that science or another field was more to her liking.

In 1964, the Civil Rights Act (Title VII) came into effect that prohibited discrimination against women in all aspects of employment in the United States. This legislation was very timely.

Contemporary Women in Geotechnical Engineering

Because this article is part of a special issue of *Geotechnical News* that commemorates the 50th anniversary of conferences in Canada on geotechnical engineering, it is important to point out that none of the contemporary women mentioned in this article attended the first conference in Ottawa in 1947. Many had not been born yet. The writer who is probably the oldest woman mentioned in this section of the article was definitely alive at the time but her travel budget for the 1947/1948 period was already committed to a trip to Mexico. (fig. 1).

It is very difficult get beyond anecdotal information when trying to determine the approximate numbers of women involved in geotechnical engineering in any given year. Most studies on women in engineering do not subdivide the aggregate data to this extent. Not all professional women in the geotechnical field are engineers, so even if statistics based upon numbers of women geotechnical engineers were available, the statistics would not provide any information on the women with geology, geophysics or environmental science backgrounds. Until the 1970s in the United States, much less than 1% of the total number of practicing engineers in all engineering disciplines were women.

Fig. 1 The author in Mexico City in January 1948. Left to right: Doris Kelley Lankford (the author's mother), the author, Howard James Lankford (the author's father), Mrs. Tinker and Mr. Tinker (fellow tourists).

In Canada it was not until 1978 that the Canadian Council of Professional Engineers (CCPE) started measuring the impact of women on the supply of engineers. Initial statistics focused on the number of women enrolled in undergraduate and graduate programs in Canadian universities. At that time, women represented about 5% of undergraduate students in engineering and 4.6% of engineering graduate students. In 1982, *Engineering Manpower News* reported that of a total 110,000 professional engineers in Canada, less than 1,400 were women. (Canadian Engineering Manpower Council 1978, 1982)

According to Matyas (1992), in 1989, women earned 53% of all bachelor's degrees received in the United States. They received 15% of the bachelor's degrees in engineering awarded that year. In 1988, 4% of the engineers in the United States were women. In contrast, 30% of U.S. scientists were women.

The Canadian Council of Professional Engineers reported in 1992 that women in Canada still comprised less than 10% of undergraduate students in engineering and that less than 2% of Canadian engineers were women.

Although the number of women in geotechnical engineering is still small, their individual contributions to the field are substantial. In order to illustrate this point, the writer contacted a small sample of women and asked them to provide information about their geotechnical work and other professional activities for this article.

Women Who Received Their First University Degree Before 1971

Dr. Suzanne Lacasse

Dr. Suzanne Lacasse is the Managing Director of the Norwegian Geotechnical Institute (NGI) in Oslo, Norway. NGI has a subsidiary office in Malaysia. She has held this position since 1991 and has been an employee of NGI since 1980. She has worked in consulting research and university teaching and in the process of doing so has worked in Canada, the United States, The Netherlands, France, England and Italy. She speaks seven languages. From 1976 to 1978, she was Head of the Soil Mechanics Laboratory at Massachusetts Institute of Technology and a recipient of the MIT Effective Teaching Award in Civil

Engineering. Dr. Lacasse is Canadian. Her areas of expertise include laboratory and in-situ testing, field observations, soil behaviour, foundation analysis, numerical analysis, probabilistic analysis, knowledge-based systems, computer programming and university teaching. Some of the national and internationally significant projects she has undertaken are: the Hibernia project in Canada; projects related to safety of tailings dams in the United States; and projects involving offshore structures in the North Sea.

She has been an Associate Editor of the *Canadian Geotechnical Journal* and is currently on the Editorial Board of the ASTM Geotechnical Testing Journal. She is a member of the Board of Directors of the Norwegian Geological Survey and of the Research Council of Norway Engineering and Sciences.

Dr. Priscilla Provost Nelson

Dr. Priscilla Provost Nelson is Program Director and Senior Engineering Coordinator for Engineering at the National Science Foundation in Arlington, Virginia. She started in her current position in August of 1996. Prior to taking on this position, she was a Professor of Civil Engineering at the University of Texas at Austin. She holds Adjunct Professor status at the University while the last two of her remaining students are finishing their Ph.D studies.

Dr. Nelson is a geologist and engineer. Her primary areas of expertise are rock mechanics, tunnelling and excavation technology and equipment. She received The Basic Research Award of the U.S. National Committee for Rock Mechanics NAS/NAE in 1993. In the same year, she was elected to the Board of Directors of the U.S. University Council on Geotechnical Engineering Research. She is a member of technical committees of the Geotechnical Division of the American Society of Civil Engineers (ASCE) and was appointed to the Division's Executive Committee in 1995. She was appointed to the inaugural Board of the Geo-Institute of ASCE in 1996. She was President of the American Rock Mechanics Association from 1995 to 1996. In 1995, she was elected to The Moles, an association for the heavy construction industry. Dr. Nelson was keynote speaker and Chair of the 2nd North American Rock Mechanics Symposium held in Montreal, Quebec in June of 1996.

Some of the projects of national and international significance that Dr. Nelson has worked on included the Superconducting Super Collider, Low Level Radioactive Waste Disposal in Texas, the Trans-Alaska pipeline and major tunnel projects: The Channel Tunnel; TARP in Chicago; and the Loma Larga tunnel in Monterrey, Mexico.

Heather J. Cross

Heather J. Cross is a hydrogeology consultant whose home base is Dartmouth, Nova Scotia. She has attained Certified Ground Water Professional status with the National Ground Water Association in the United States. She is a member of the Well Construction Advisory Board that provides advice to the Nova Scotia Ministry of the Environment. In addition to her consulting activities she is an Adjunct Professor at the Technical University of Nova Scotia where she currently teaches a graduate course in Groundwater Chemical Quality.

She has also taught hydrogeology courses as a Special Lecturer at Dalhousie University. From 1974 to 1980 she was employed as a hydrogeologist with the Nova Scotia Department of the Environment. As a consultant she has undertaken studies on the environmental effects of uranium mining, milling and waste management, detailed contaminant studies, peer reviews of environmental consulting reports, groundwater evaluation and water supply assessment.

Mona Bechai

Mona Bechai is a Manager, Civil Field Services at Ontario Hydro in Toronto, Ontario. She is currently responsible for civil maintenance, instrumentation, inspection and monitoring of Ontario Hydro hydroelectric dams. This work involves consideration of needs for 247 dams having an average age of more than 50 years. She has worked on developing options for deep disposal of low to intermediate level nuclear wastes and was involved in the design and construction of the first reinforced earth wall to be built under water, that is, without dewatering.

She has served as a Regional Director of the Engineering Geology Division of the Canadian Geotechnical Society and is currently a member of the Executive of the Southern Ontario Section of the Society.

Anna Lankford Burwash

Anna Lankford Burwash is an American-born Canadian citizen. Her primary areas of geotechnical interest are in muskeg and engineering in northern environments. Her professional career has included work as an engineering consultant, management consultant, university researcher and as a civil servant in three Ontario ministries. She currently holds a senior policy position in the Ministry of Health.

She was a Regional Director (Atlantic Provinces) of the Canadian Geotechnical Society from 1973 to 1976. She has served on the Associate Committee on Geotechnical Research of the National Research Council of Canada and on the Editorial Board of the *Canadian Geotechnical Journal*. From 1980 through 1987 she was a member of ASTM D18.18 Subcommittee on Peats and Other Organic Soils and served a two-year term as Chair. She has been very active in the Technical Council on Cold Regions Engineering of the American Society of Civil Engineers. She was appointed to the Council's Executive Committee in 1988 and was its Chair in 1991/92. She continues to be a member of three of the Council's administrative committees: Awards, Publications and Education.

Women Who Received Their First University Degree from 1971 to 1980

Dr. Deborah J. Goodings

Dr. Deborah J. Goodings is a faculty member in the Department of Civil Engineering at the University of Maryland in College Park, Maryland. She is currently on a sabbatical leave at Cambridge University in England. She teaches undergraduate and graduate students and conducts research concerning landslides, sinkholes, reinforced soil, cratering, grouting, geo-environmental problems and cold regions geotechnique. Before becoming a university professor, Dr. Goodings worked on the Tarbela Dam in Pakistan for two years. Before that she was a field engineer for the Ontario Ministry of Natural Resources where she was involved in field mapping and stability assessment of slopes (Champlain Sea Clay) on the South Nation River.

Dr. Goodings' Ph.D thesis work at Cambridge University on centrifugal modeling of slope failures was acknowledged by Dr. A.N. Schofield in the Twentieth Rankine Lecture presented in 1980. (Schofield 1980)

Dr. Sandra L. Houston

Dr. Sandra L. Houston is Professor and Interim Chair of the Department of Civil and Environmental Engineering at Arizona State University. Her major subject areas of interest in geotechnical engineering include arid-land soils, unsaturated soils, collapsible soils, problem soils, cemented soils, saturated and unsaturated groundwater flow and high-temperature behaviour of soils. Dr. Houston is very active in the Geotechnical Division of the American Society of Civil Engineers as a member of the editorial board of the ASCE *Journal of Geotechnical Engineering*, Chair of the Unsaturated Soils Subcommittee and a Control Group member of the Soil Properties Committee. She is Secretary of the Unsaturated Soils Committee of the International Society of Soil Mechanics and Foundation Engineering and Secretary of the Board of Directors of the United States University Council for Geotechnical Engineering Research.

Sue E. Evison

Sue E. Evison is a senior geotechnical engineering consultant with AGRA Earth and Environmental Limited in Calgary, Alberta. Her primary areas of geotechnical expertise are in numerical modelling, slope stability, tunneling and trenchless technology. In her work on the McKnight Boulevard sewer rehabilitation, a world precedent was set for materials handling in a trenchless cured-in-place relining technique. She has been involved in complex numerical analyses in hydrogeological, geotechnical and structural engineering applications. Examples include: seepage studies for analysis of flow through a proposed 800-metre-long semicircular rockfill cofferdam and underlying highly fractured bedrock into a proposed open pit excavation at a uranium mine; detailed finite element simulation of soil-pipe interaction for a high-pressure gas pipeline in soft Bangkok clay in Thailand; and detailed two-dimensional finite element simulation of soil-structure interaction for a seabed-founded structure in the Beaufort Sea.

She is a Director (Southern Alberta) of the Canadian Geotechnical Society. She has been very active in the Association of Professional Engineers, Geologists and Geophysicists (APEGGA) since 1987. She was recently elected as a member of the APEGGA Council.

Anne S. Poschmann

Anne Poschmann is a principal in Golder Associates in Mississauga, Ontario. She is responsible for technical and administrative control of geotechnical engineering projects with specific emphasis on major transportation networks and municipal services.

The technical scope of her activities has included feasibility studies, geotechnical investigations, foundation design, and testing and monitoring during construction. The range of transportation and municipal service projects has included expansions of the Toronto Transit Commission subway system; contraction, relocation or rehabilitation of major bridges in Ontario usually in urban areas; roadworks design; and sewers. She is often involved in very complex projects involving use of deep foundations or tunnelling.

Anne was a Director and Treasurer of Consulting Engineers of Ontario from 1991 to 1994. She has been very active in the Southern Ontario Section of the Canadian Geotechnical Society and has been a member of the National Engineering Week-Ontario Steering Committee from 1993 to the present.

Women Who Received Their First University Degree from 1981 Onwards

Dr. Mary Roth

Dr. Mary Roth is an Assistant Professor at Lafayette College in Easton, Pennsylvania. Lafayette College does not offer graduate study so all of her students are undergraduates. Dr. Roth received her own undergraduate degree at Lafayette.

She is very active in committees of the Geotechnical Division of the American Society of Civil Engineers. She is presently a Control Group member of the Earth Retaining Structures and the Geotechnical Safety and Reliability Committees.

From 1994 through 1996 she was a member of the Geotechnical Specialty Conference organizing Committee and co-editor of the proceedings of the Specialty Conference held in Madison, Wisconsin in August of 1996.

Susan W. Hollingshead

Susan W. Hollingshead is employed as a Geotechnical Engineer/Quality Coordinator by Klohn-Crippen Consultants Ltd. in Richmond, British Columbia. She is a Registered Professional Engineer in Alberta, the Northwest Territories, Ontario, and the Yukon Territory.

She is a Registered Professional Engineer and a Registered Geoscientist in British Columbia. She is currently involved in developing a formalized quality management system for the company.

Her geotechnical experience includes: design of shallow and deep foundations for residential, commercial, and industrial structures; design review of soil-structure interaction problems involving pipelines founded in soft ground; preparation of technical specifications for excavation, fills, piles and vibro-replacement; liquefaction assessments; construction management; soil investigations; field instrumentation and testing. She was Chair of the Vancouver Geotechnical Society in 1993/94.

Jodi Everard

Jodi Everard is a Project Engineer in the Geotechnical Division of AGRA Earth and Environmental Ltd. in Burnaby, British Columbia. She has been involved in various aspects of geotechnical and environmental engineering since 1992. Her areas of specialization include: the use and interpretation of in-situ testing tools for both geotechnical and geo-environmental applications; site assessment; soil mechanics and foundation engineering; and dynamic and earthquake engineering. At AGRA, she has been involved in a range of projects including design of foundations for commercial and industrial structures; slope stabilization; design of waste dumps, tailings dams and heap leach facilities; seismic design of foundation systems and bridges; dynamic analysis of machine foundations, excavation and shoring design; and design and construction monitoring of landfill and leachate collection facilities.

Prior to her studies in civil engineering and geotechnical engineering, she received a bachelor's degree in mathematics. She is fluent in English and French and conversant in Spanish. She has worked on projects across Canada and in the United States, Australia, Russia, Finland, Estonia and South America. In 1995/96, she was Chair of the Vancouver Geotechnical Society.

The women whose work is described briefly in this article, represent a small sample of women in geotechnical engineering. They and their growing number of female colleagues around the world continue to bring their imagination, vision and commitment to geotechnical engineering.

Acknowledgment

The writer would like to thank all of the contributors. They are Mona Bechai, Heather Cross, Jodi Everard, Sue E. Evison, Dr. Deborah J. Goodings, Susan W. Hollingshead, Dr. Sandra L. Houston, Dr. Suzanne Lacasse, Dr. Priscilla Provost Nelson, Anne Poschmann, and Dr. Mary Roth. She would also like to thank her geotechnical colleagues and friends for their encouragement and support over the past 27 years.

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ANNA LANKFORD BURWASH was born in Maryland. She graduated in civil engineering from Carnegie Mellon University, Pittsburgh in 1968 and with a professional development degree in engineering from the University of Wisconsin-Extension in 1981. In 1993, she received a certificate in gerontology from Ryerson Polytechnic University.

Anna moved to Canada in 1968 and became a Canadian citizen in 1974. She has been employed in engineering consulting in New Brunswick and Alberta. Her initial experience in applied research studies in muskeg and permafrost was gained at the Muskeg Research Institute of the University of New Brunswick. Her geotechnical consulting experience was obtained as an employee of Geocon Ltd. in Fredericton, New Brunswick and Hardy Associates Ltd. in Calgary, Alberta.

In 1980 Burwash established a consulting firm in Calgary that provided management consulting services including assistance in recruiting geotechnical personnel. In 1987 she became a technology consultant in the Ontario Ministry of Industry, Trade and Technology. In 1988 she became a manager of the Ministry of Community and Social Services. Since 1990 she has been a project manager in the Long-Term Care Policy Branch, Ministry of Health.

Ms. Burwash has had extensive involvement in technical societies and committees, including the Canadian Geotechnical Society, *Canadian Geotechnical Journal*, National Research Council Associate Committee on Geotechnical Research, Engineering Institute of Canada, American Society for Testing Materials, and chair of the Executive Committee of the Technical Council on Cold Regions Engineering of the ASCE.

Embankment Dams in Canada

Victor Milligan and Donald H. MacDonald

This paper reviews the design and construction of embankment dams in Canada. It does not discuss tailings dams which are reviewed elsewhere in this volume. Specific aspects of the James Bay project are also reviewed in a separate paper.

Introduction

The first dam of any size constructed in Canada was the 19 m high Jones Falls masonry dam on the Rideau River in Ontario, completed in 1832 and credited to Lt. Col. John By. But it was not until 1895 that the first earthfill dam of any substance was built. This was a water retaining structure, the Goldstream Dam, for the Greater Victoria Water District, British Columbia. For the next 50 years prior to 1945, few earthfill or rockfill dams were constructed and those built were of comparatively low height. However after about 1950, the number and size of embankment dams markedly increased. This is illustrated in Figure 1, which plots the number of embankment dams more than 15-m in height built per decade since 1900. The increase in number of embankment dams constructed since 1950 is remarkable, as is the trend of increase in height since that date. An example of this is that by the decade 1950-60, the highest fill dam to date was the Kenney Dam in British Columbia, a 104 m high rockfill embankment; since then 10 fill dams exceeding this height have been built, the highest being Mica, an earthfill structure 243 m high completed in 1972, also in British Columbia.

The majority of the dams now built are of the embankment type and most have been built for hydroelectric power generation. Two projects accelerated the design and construction of fill dams: in the period 1968-72, some 88 earth and rockfill dams and dykes (only 50 per cent of these being over 15 m in height), totalling about 64 km in overall length were built for the Churchill Falls power project in the Canadian Shield of Labrador; in the period 1976-82, over 80 earth and rockfill dams and dykes were constructed in Quebec, also in the heart of the Canadian Shield, as part of the James Bay hydroelectric project. Many of these dams were of significant size, the highest being L6-2 dam, 168 m high rockfill completed in 1978 on La Grande Rivière.

Influence of Physiography and Geology

Canada may be divided into four main physiographic and geological regions distinguished by variations in topography and geology. These are the Canadian Shield, the Appalachian Region, the Plains Region and the Cordilleran Region. The Canadian Shield, which extensively covers much of the northern and eastern parts of the country, is a peneplained region comprised of igneous, metamorphic and some volcanic and sedimentary rocks, all of Precambrian age. At its southerly and western border, these Precambrian rocks dip beneath thick beds of sedimentary shales, limestones and sandstone of Paleozoic and Mesozoic age which constitute the Plains region. The Cordilleran rocks to the west comprise deformed younger sedimentary and metamorphic rocks, as well as volcanic intrusions together with igneous rocks.

Hydroelectric developments in the Cordilleran region, principally in British Columbia and their counterparts in the Canadian Shield, have largely dominated the development of large embankment dams in Canada. This is not surprising as, apart from the St. Lawrence River, the three largest river flows are the Mackenzie draining into the Arctic Ocean and the Fraser and Columbia Rivers in British Columbia flowing to the Pacific. The total river flows in British Columbia correspond approximately to the total river flows from the Canadian Shield into Hudson Bay.

Embankment dams, to be economical need local availability of suitable construction materials. As over 95 per cent of the land surface in Canada has been glaciated, glacial deposits, fluvioglacial and glacio-lacustrine sediments provide most of the construction materials available together with quarried rockfill. The most common glacial deposit is till, which forms perhaps as much as 75 per cent of the surficial deposits in Canada even in areas later subjected to late-glacial or post-glacial marine or lacustrine inundations. Tills are complex deposits and their properties are largely determined by the nature of the parent bedrock up-ice from the local till deposit and by the mode of deposition. It is the variable nature of these tills and associated glacial sediments together with the foundation rock and the effects of climate which engender problems in the construction of embankment dams. Some problems, typical to Canada, are described. They provide instructive examples of the effective solution of design and construction problems.

Dams on Weak Foundations

Two examples of dams built successfully on weak compressible foundations can be attributed to K. Terzaghi, whose name has been given to what was originally called "Mission" Dam. This 61 m earth and rockfill structure, built on the Bridge River in British Columbia, is founded on over 150 m of alluvium comprising soft clay underlain by sand and gravel. Completed in 1960, it involved a deep clay-cement grout curtain and an upstream soft deformable clay blanket to inhibit seepage. Of particular interest is the use of polyvinyl chloride sheeting almost 10,000 sq. m. in area to sheath the clay blanket on the upstream face of the dam so that the clay could squeeze into any transverse cracks which developed. This is possibly one of the earliest uses of geosynthetics in major dam construction.

Terzaghi was also consultant on the Cheakamus Dam, an earth and rockfill embankment some 28-m high built in 1957 in British Columbia and founded on a variable thickness of relatively recent landslide debris, a heterogeneous deposit which included tree trunks!

The precedence for building on sensitive marine clays was probably Bersimis 2 in Quebec, the auxiliary dams being built in 1957-59. Weathered marine clay was also used as core material.

On the James Bay project in Quebec, many kilometres of glacial till dykes were also successfully constructed on deposits of sensitive marine clays. Another notable example is given by the dykes of the Manicougan-Outardes complex, known as Outardes 2.

Possibly one of the most striking examples of a fill dam safely accepting settlement is that of the Duncan Dam, built on the Columbia River in British Columbia, 1964-67, over glacio-lacustrine deposits several hundred metres thick, containing extensive silt layers. Significant settlements along the dam's axis had been anticipated during design, but severe cracking occurred during construction due to differential settlements of over 4-m adjacent to the left abutment where the deposits were only marginally over-consolidated. (The dam at maximum height is only 39-m high, measured above foundation level). Large transverse cracks through the core developed necessitating sealing, re-design of the dam section, re-locating the core and flattening the slopes. It is a credit to those concerned that the dam has performed satisfactorily to the present.

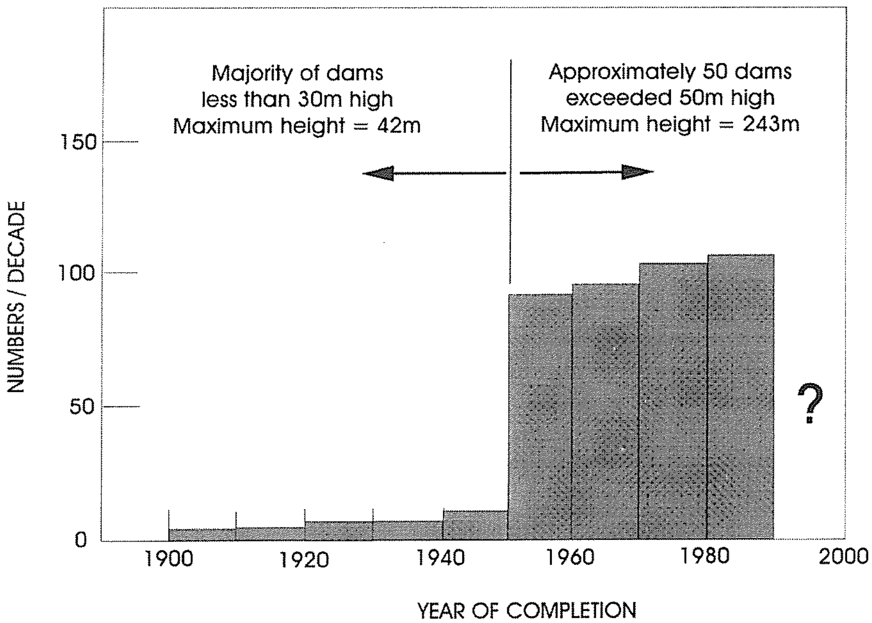


Fig. 1. Embankment dams (higher than 15m) built per decade in Canada since 1900.

While, in comparison to the previous examples, the Gardiner Dam, a 64-m high earthfill structure built on the South Saskatchewan River, cannot be considered to rest on a "soft" foundation. The Bearpaw shale on which it is founded is nevertheless highly plastic and deformable with pre-existing shear planes. About 2 m of vertical settlement and over 2 m of lateral displacement occurred under the central section of the embankment during construction 1964-68. Post-construction lateral deformations at the downstream toe are related mainly to annual cyclic changes in reservoir level and have now decreased to the order of 10-20 mm/year. The design of this dam is remarkable in that it preceded much of our current understanding of residual shear strength and the behaviour of highly overconsolidated clay-shales.

The design and construction of more recent dams of equal or greater height in Saskatchewan and Alberta such as Dickson Dam (1987) and Oldman Dam (1993), founded on horizontally bedded shales and sandstones, containing weak bedding plane shears, have benefited from the experienced gained from Gardiner Dam.

Effects of Frost

Climate is a major factor in embankment dam construction. Few countries suffer the effects of cold weather more than Canada and particularly in the eastern Canadian Shield region. Frost and freezing weather affect dam construction in a number of ways—during borrow excavation and fill placement, by its effect on the core and by the effect of thawing of frozen foundations, such as permafrost. The optimum utilization of machines and men in a climate restricting the placement of fill, sometimes to only 2 months a year, stimulates innovative solutions.

At Manicougan 3, an earthfill structure 108-m high on the Manicougan River (1975), it was necessary to place glacial till core material in prevailing cold, rainy, short construction seasons. The till was non-plastic and wetter than the optimum water content. To extend the construction season, the water content of the till was reduced by the use of a rotary kiln dryer; light vibratory smooth-faced rollers were used to compact the till producing a moist deformable core in situ. This has performed satisfactorily to date.

Similarly, the dykes of the Outardes 2 hydroelectric scheme, adjacent to Manicougan 3, were constructed with an impervious core comprised of a local clay mixed with sand, which had been dried in a rotary kiln to develop a mixture at near-optimum water content.

Hydroelectric development of the Nelson River in northern Manitoba was complicated by the widespread presence of discontinuous permafrost. Ice in the form of lenses or inclusions was conspicuous in lacustrine deposits. Where encountered in glacial till, it was difficult to detect because of the very dense nature of the till. The presence of ice in till, which must be excavated, makes removal even more difficult than normal, necessitating drilling and blasting. When the materials are then exposed to summer temperatures they soften quickly exacerbating problems of handling and placement.

Frozen till which exists beneath extensive shallow dykes, thaws after placement and impoundment, but because the ice content in the very dense till is often less than the overlying soils, normally only minor settlements result from thawing of the till. Where, however, lacustrine soils are ice rich, settlements can be significant and allowance had to be made in design. An example of the design and construction of such dyke fills is the Kelsey project completed in 1960. Sand drains were installed in the foundation to improve stability during thawing and the dykes were built of sand to accommodate settlement. These dykes provided experience and precedents for subsequent work at Kettle Rapids in 1969 and Long Spruce in 1977.

Not all tills affected by frost are equally dense. The broadly graded silty tills on the Labrador Plateau exist at a low density, probably as a result of their method of deposition. These loose tills, combined with high groundwater conditions and a cold, wet construction season, are difficult to handle. Problems of instability of these tills were encountered during the construction of the Sandgirt-Lobstick dykes of the Churchill Falls project in 1969-60, involving costly disruption to normal construction operations. It is significant that frost penetrations of over 5 m were measured. The fact that about 65 km of dykes, ranging in height from 10 to 30 m high, were successfully completed by 1971 is a tribute to both engineers and contractors.

A striking example of the long-term behaviour of an embankment dam built on discontinuous permafrost is Waterloo Dam on the Charlot River in northern Saskatchewan. This earthfill structure built in 1961, with a core of uniform silt and some 19-m high, behaved well under initial impoundment. With time, the left abutment built on permafrost, induced thawing, subsequent leakage and sloughing of slopes. These were remedied, but over the next two decades, repeated annual severe winter freezing caused almost permanent ice lensing and ice boils in the downstream portion of the silt-till core material. The situation was remediated by partial excavation and replacement of the core and the provision of styrofoam insulation to the upper part of the central section of the embankment.

Use of Dumped Fill Under Water

In a number of instances throughout the world, cofferdams have been constructed by progressively end-dumping rockfill and finer materials directly into water. In Canada, this technique has been extended by end-dumping till and sand and gravel to form permanent dam structures.

Early experience gained in building cofferdams, of till in water about 10 m deep or less, for the St. Lawrence River project in the 1950s was extrapolated to construction of the Hugh Kelleyside Dam (Arrow Lakes) on the Columbia River in British Columbia in 1960-68. At the site, the riverbed consists of sands and gravel alluvium over 150 m deep containing lenses of openwork gravels. As controlled dewatering was not considered to be economically practicable, the construction of the dam (to be 59 m at final height) involved placement of substantial portions of the dam fill under water. Till was bottom dumped from barges of large capacity (230 m^3), hinged to split longitudinally, to form an upstream blanket. Till was also placed by end dumping from trucks on the face of a previously dumped sand-gravel portion of the dam. The till was dumped in windrows at the edge of the sand-gravel fill. Bulldozers then heaped the till until a slide occurred. A general fill level about 1.5 m above river level was found most suitable for construction, the depth of water being about 10—15 m deep. The till was placed at a high air content and at a water content virtually that of the borrow pit, which was close to Proctor optimum. Dry unit weights of the till placed under water were about 95 per cent of the unit weight of the same till compacted by rolling. After almost 30 years of operation the performance of the dam is satisfactory.

Another example of this form of construction, as applied to winter conditions, is given by the Twin Falls hydroelectric project on the Unknown River in Labrador. Because of the limited period of suitable weather available for fill placement, the most practicable means of construction for the dam, less than 15-m in final height, was to dump a rockfill section across the river and then dump locally available till along the upstream face of the rockfill until a seal was obtained. Placing of the rockfill was carried out through the winter of 1961-62 and dumping of till commenced in April, 1962. Ice in the river had to be broken up by blasting, and care had to be taken to minimize the possibility of burying blocks of ice in the fill. End-tipping of till from trucks continued on a round-the-clock basis despite blizzards; low temperatures generally prevailed below freezing until June when they moderated. At that time, it was possible to place and compact till above water level to bring the dam close to final elevation. The final upstream slope of the dumped glacial till was about 3H:1V. When water levels were raised the following year, sinkholes developed in the till and there were substantial losses of water. The sinkhole development is attributed to thawing of the dumped till and possibly to some ice blocks trapped in the mass. Further progressive dumping of the till upstream was sufficient to fill the depressions and provide a watertight zone to the dam.

The technique of dumping fill under water was used to initiate the construction of the Gardiner Dam (1964), previously discussed, by dumping sand and gravel into the river, less than 3-m deep. It was also used to form the Eastmain Dam, upstream of the L6-2 reservoir in the James Bay project. The dam was relatively modest in height (31 m), but construction of the Eastmain riverbed section was complicated by the presence of relatively weak fine-grained soils in the foundation. Sand and gravel fill was dumped into the river to form a base for the dam, the rate of placement being controlled by monitoring piezometric response in the underlying weak soils. When the fill was above river level, it was compacted by vibroflotation to ensure a relatively dense base on which to construct the remainder of the conventional earthfill embankment (1980).

An approximate synthesis of Canadian experience in dumping tills under water to form dams (and cofferdams) is illustrated by Figure 2. The range in gradation of tills commonly dumped is plotted. In general, such tills performed satisfactorily both during construction and on drawdown (up to 10-15 m). The underwater stability of most of the tills dumped is attributed to low initial porewater pressures resulting from placement at relatively low degrees of saturation, but progressive slips occurred during consequent dumping causing increasing saturation of the till. Slips appear to be more frequent when "finer" till is dumped and pore pressures tend to be high.

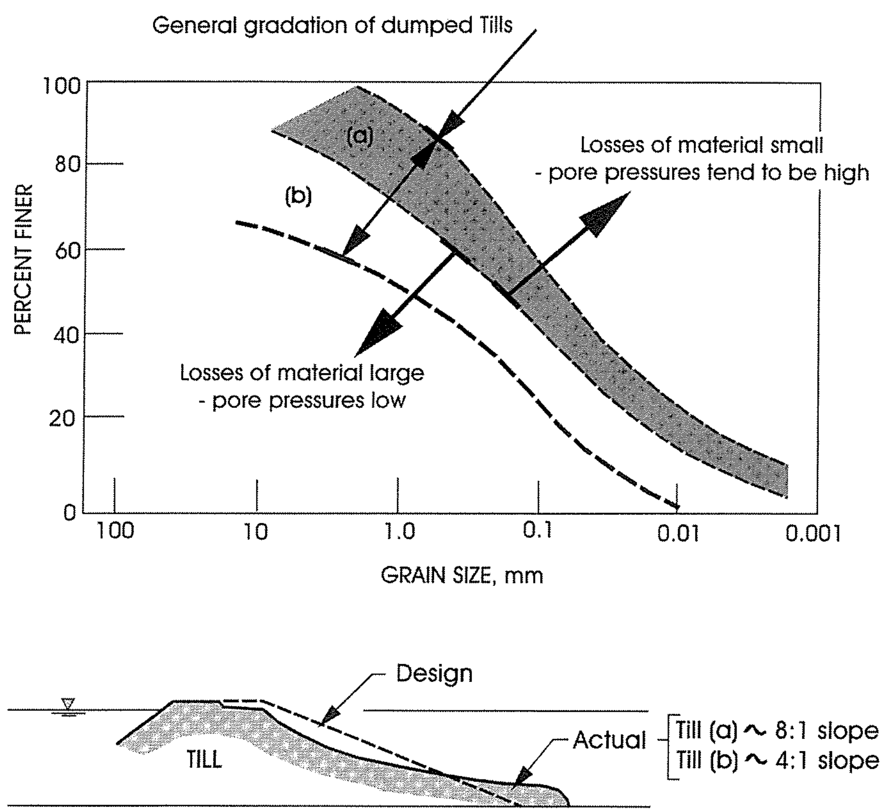


Fig. 2. General experience with dumped tills under water.

The final slopes resulting from such progressive slips tend to approach 8H:1V, as compared to slopes of 3 to 5H:1 when coarser material is dumped. A tentative guideline for the division between "fine" (a) and "coarse" (b) is suggested, based on experience.

Common Problems with Coarse Till Cores

It is a frequent practice to make a rule-of-thumb distinction between "fine" and "coarse" tills when used as core material in embankment dams. While inexact, it can be assumed that most tills in the Canadian Shield region, and to a lesser extent in the Cordilleran region, tend to be "coarse", as compared to the more cohesive "fine" tills in the Appalachian and Plains regions. Both kinds of till can be compacted satisfactorily to form dense fills of high strength and relatively low permeability, but differ somewhat in behaviour under seepage gradients. The coarser broadly-graded tills are generally low in plasticity and tend to segregate during placement. This characteristic, together with their broad gradation, makes it difficult to determine the optimum gradation for filter and transition materials. As a consequence, seepage losses associated with sinkholes in the till core are not uncommon and have been widely experienced in Eastern Canada, and also in Scandinavia where similar tills have been used for cores. Examples of note are reported for the Churchill Falls dykes (1968-72); for several dams and related dykes of glacial till at the Wreck Cover hydroelectric project, Nova Scotia (1973-78); on the James Bay project (1976-83); and at several other smaller dams in Ontario. It should be noted most of the embankments affected were generally of rockfill with till cores; others were usually a homogeneous till section. Most of the sinkholes developed at relatively low average hydraulic gradients.

The 21 m high homogeneous Three Sisters Dam in Alberta, founded on talus and deep glacio-fluvial deposits gives an early example of repeated sinkhole formation. Constructed in 1951, several sinkholes were first observed in 1974 when the reservoir was drawn down. However, a great number of sinkholes occurred in the upstream blanket, which consisted of silty till placed directly on the foundation deposits. Additional sinkholes developed for a number of years thereafter despite repeated remedial action.

Today, the reservoir operates at reduced head and sinkhole activity has been markedly reduced, causing no concern.

Dams on Pervious Foundations

Pervious foundations demand the use of one or several expedients to control seepage and to inhibit potential instability caused by seepage. Positive cut-off walls, downstream drainage, relief wells, upstream blankets, complete excavation and replacement of the pervious foundation materials, and rock grouting have all been used.

Hugh Keenleyside Dam on the Columbia River is an example of an embankment founded on deep pervious deposits, but where downstream flows in the river were not just permitted but mandatory. No cut-off was provided for the dam, and underseepage flows were controlled by means of an upstream blanket, downstream drainage and relief wells.

For the case of the Terzaghi Dam, previously mentioned, it was necessary to inhibit underseepage in the variously pervious foundation, and this involved the construction of a 150 m deep clay cement grout curtain through alluvium to bedrock using techniques new for Canada at that time (1960). Similar techniques were used at Outardes No. 4 Dam (1968) to form a grouted cut-off in talus material some 25 m thick, containing large blocks of rock up to 3 m diameter, the voids between blocks being incompletely filled with fluvial sands, gravel and silt.

In 1972, construction of the Bighorn Dam, a 92 m high earthfill embankment on the North Saskatchewan River in Alberta, necessitated construction of a concrete cut-off through 65-m of alluvial sands and gravels. The wall, 600 mm, thick was constructed using a bentonite slurry trench excavated by clamshell and percussion tools. During winter, construction was continued from within a heated enclosure.

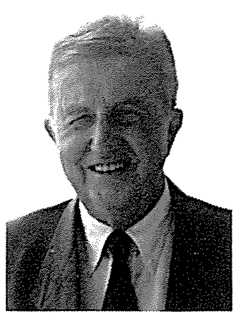
The same method was initially considered for the Manicougan 3 Dam to be founded on over 120 m of sands, gravel and boulders. The depth of cut-off, 121 m, exceeded the maximum height of the earthfill embankment, 107 m, and was to be the deepest such cut-off ever installed to that time (1975). After several trials, the design adopted was a double cut-off concrete pile wall, installed using bentonite slurry and comprising two rows of piles and panels. In the deepest centre section each row consisted of interlocking piles, 600 mm diameter; on the flanks, panels 600 mm wide and 3.5 m long were formed. The rows were about 2.5 m apart and were joined by cross-walls where the piles and panels meet. It was intended that, where required, the alluvium between the rows would be then grouted. To demonstrate the practicability of the method, a similar wall 75 m deep was first built beneath the upstream cofferdam at Manicougan 5, 120 km upstream of the site.

In contrast to the examples discussed above, the use of a cut-off was not adopted at the site of Lower Notch Dam on the Montreal River in Ontario. The dam, a 123 m high rockfill embankment with a central core, was located within a deep narrow gorge. Below riverbed level the sediment-filled gorge was 76 m deep with a width of only 24 m at the top reducing to less than 6 m wide at the bottom. All of the pervious gorge infill sediments were excavated and replaced with impervious and other fills. The excavation was complicated by the near vertical walls of the gorge containing shear zones, areas of loose weathered bedrock and open joints, resulting in the need for extensive rock treatment and modification of the rock geometry to minimize potential core cracking.

The overall permeability of rock foundations, in comparison with that of unconsolidated fluvial sediments, is not normally considered to be a major concern; however, on occasion, the need for more than simple grout treatment occurs. As an example of extreme need, the Grand Rapids hydroelectric project on the Saskatchewan River in Manitoba (1965) represents the most extensive rock grouting work ever carried out in Canada. The reservoir formed covers over 550,000 hectares and extends some 130 km westwards from Lake Winnipeg. The reservoir area and over 25 km of dykes were extensively grouted to inhibit seepage through underlying karstic dolomitic limestones. This extensive grouting programme took several years to complete and has few parallels in North America.

Conclusion

The paper attempts to illustrate that problems of design and construction of embankment dams in Canada are generally related to geology, particularly glacial geology, and to several climatic conditions. Solutions to these problems as typified by the examples in this paper, have been innovative, advancing the state-of-the-art of building embankment dams and providing valuable experience to the profession worldwide.



VICTOR MILLIGAN, born in Northern Ireland, is a civil engineering graduate of Queen's University, Belfast in 1951-52. He was awarded a post graduate research fellowship to Purdue University in 1954-55.

Milligan first worked in Scotland as a site engineer on a fossil fuel power station. In 1955 he joined Geocon (a subsidiary of Foundation Company of Canada) in Montreal, becoming assistant chief engineer. In 1960, with Dr. Hugh Golder, they formed Golder and Associates in Toronto, which has grown into a major Canadian geotechnical firm with offices throughout the world. After serving as president, chief executive, and chairman, Milligan retired from the company in 1994.

Currently he serves on consulting boards for embankment dams in Canada, the US, and internationally-particularly Thissavros Dam, Greece, the highest rockfill dam in Europe. He also acts as a consultant on Singapore Mass Rapid Transit and on Athens Metro.

Milligan has contributed to numerous technical societies and received many awards. In the Canadian Geotechnical Society, he has won both the Legget and Meyerhof awards, and in 1996 presented the R.M. Hardy Keynote Address. He is a recipient of the Engineering Institute of Canada Julian C. Smith Medal for contribution to the development of Canada.

Acknowledgements

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DONALD H. MACDONALD was born and educated in Ontario, graduating in civil engineering from the University of Toronto. He subsequently took graduate work at Cornell University and Imperial College of Science and Technology, finishing with a Ph.D. from the University of London.

Except for four years on the design and construction of Toronto's first subway, MacDonald's entire career was spent with the Acres organization, in a variety of technical, supervisory, and executive roles. He has participated on numerous hydropower and water resource projects in all parts of Canada and in many countries abroad. He has been associated with the design and construction of many dams and dykes in Canada, including Churchill Falls, Mica, Nelson River projects, and others in Ontario, Quebec, the Maritime Provinces, and Western Canada.

Dr. MacDonald has participated extensively in technical and professional societies, occupying senior roles in the Tunnelling Association of Canada, Consulting Engineers of Ontario, and the Canadian Congress on Large Dams (CANCOLD). He has authored a number of publications, and has been the recipient of a number of awards and honours. Aside from engineering, he has been extensively involved in the work of a number of education, artistic, and charitable institutions and organizations.

Tunnel Engineering in Canada

Raymond P. Benson

Introduction

Canada is a vast country covering an area of almost six million square kilometers, exceeded in size only by Russia. Spanning five time zones from east to west and reaching from the central plains of the continent to the high arctic, development of its transportation system and industrial base has been, and still remains, an enormous challenge. Tunnels have helped in this development, but none were constructed during the first three centuries following the discovery and settlement of Canada. Up to the end of the eighteenth century the movement of people and goods was by canoe and overland portages, with motive power by horses and men.

The first steamboats began operation in 1809 on the St. Lawrence River, where the tidal reach ended at Quebec City. By 1825 Quebec City was the second largest city in the Dominion with a population of 22,101, second only to Montreal by a mere 256 souls. York, yet to be renamed Toronto, was a distant third with 1,677. Railways became the overland link between water routes plied by canoes and steamships, initially replacing the longer and more difficult portages, then expanding to regional carriers connecting new cities and towns to river and lake ports, and then to rapidly expanding commerce with the United States. As more difficult terrain was encountered, the need for tunnels became compelling. Little wonder that the great majority of tunnels in Canada over the next century would be for railways, and in achieving connection across the entire nation some of these tunnels were spectacular feats of engineering.

The first tunnel in Canada was completed in 1860 near Brockville, Ontario to provide river access for the 75-mile-long Brockville to Lac Chats railway line. It was short, just over one-half of a kilometre, similar to a number of other tunnels built during the nineteenth century.

Up to the mid-twentieth century major tunnels in Canada were still associated with railways, but the demands of developing cities and regional transportation systems required tunnel connection to the U.S. In 1915, a twin-tube sunken tunnel between Detroit and Windsor completed the second major underwater connection to the U.S. The famous St. Clair railway tunnel between Sarnia and Port Huron had already been in operation since 1891.

The greatest number of tunnels in any country is usually required for water supply and sewage systems. Normally of smaller diameter and easily accessible for construction, their contribution to improved design and construction methods has been overlooked. Thus, in Canada, by far the greatest number of tunnels is represented by the mundane municipal infrastructure required in every city and almost every major town. It is likely that no complete listing of these tunnels will ever exist.

Similarly for mines, tunnels are a normal part of underground operations. The number and size of these tunnels outrank those required for civil works by a factor of about 10. Much has been contributed to the science of tunnelling by mining engineers and contractors, but limited documentation exists. As well, mine tunnels are often abandoned and forgotten when mining is complete. Nevertheless, with Canada's tremendous mining history, their contribution to the tunnelling industry has been strong. The Canadian mining industry is known throughout the world, especially in hard rock exploration and tunnelling. Many of these methods have been transposed into the civil engineering and contracting fraternity.

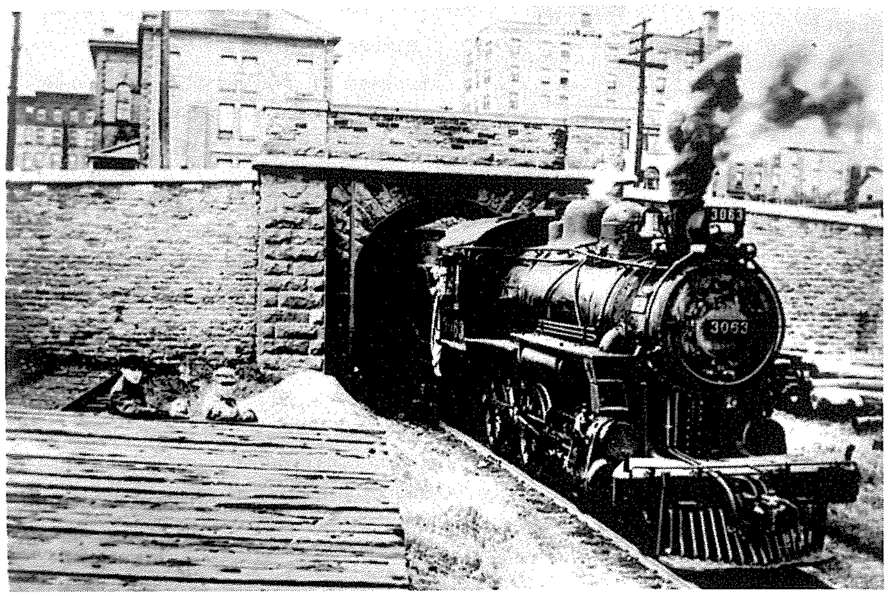

Photo 1. Brockville Tunnel (Courtesy City of Brockville Museum).

The need for energy is fundamental to a developing country. Up to the twentieth century such energy was supplied by the endless quantities of wood and coal available in Canada. However, the capture of hydroelectric power from rivers and waterfalls was an ideal way to provide the energy necessary for the developing cities, and for their associated industrial needs. Tunnels are a natural part of many hydroelectric projects, and their use began in the late 1800s. At Niagara Falls, the first Ontario Hydro plant was installed in 1895, tucked just downstream of the falls on the Canadian side of the Niagara River. Many other hydroelectric plants would be built in the twentieth century throughout Canada, with great tunnels that rival the largest and most complex in the world. In the latter half of the twentieth century some of the world's largest hydro projects, with the powerhouses sited underground, would be constructed in Canada. At present, the two largest in the world, Churchill Falls and LG-2, provide energy to the power grid of Quebec. Many more remain for future construction, as less than 50% of the hydroelectric power potential of Canada has been developed.

Underground rapid transit systems are becoming essential for major cities and Canada is no exception. Beginning in the 1950s with Toronto, transit systems now exist in Vancouver, Calgary, Edmonton, Toronto and Montreal. Tunnelling is often the best solution for such systems, helping not only to reduce surface congestion, but to limit the impact of winter weather.

Tunnels have also been used to provide solutions for diverse problems and many more uses not yet recognized remain for the future. For example, tunnels for exploring ways to store radioactive wastes; tourist facilities for inspection of Niagara Falls; storage and transfer of goods; safe havens for people; access to hot springs in snow-covered mountains; secure military establishments; and other resourceful ideas not yet tried. The future of tunnelling is bright indeed.

Photo 2. Planning Group for ICR, Sir Sandford Fleming seated at right (Circa 1870, National Archives).

Tunnelling in the Nineteenth Century

All the known tunnels built in the nineteenth century were associated with railway construction, beginning with the Brockville Tunnel built between 1854 and 1860. This tunnel is 527 metres long, and was fitted with oak doors at each end, reportedly to maintain the temperature and to keep out wandering livestock. Stone masonry was used near each end to support soil sections, with an unlined central portion in competent sandstone (Photo 1). During it's almost 100 years of operational history, the invert was lowered to accommodate increasingly larger trains. The tunnel was transferred to the CPR in 1881, then sold to the city in 1983. The last ceremonial train passed through the tunnel in 1969. The tunnel was reported by Leggett (1973) to be in good condition, and a late 1996 telephone call to the City confirms this as a current state. It is now used as a tourist attraction.

The opening words of the BNA Act proclaimed on July 1, 1867, required construction of an Intercontinental Railway to consolidate Canada. Thus was born the Intercontinental Railway Company (ICR) and planning began on completion of the transcontinental railway, which would finally be known as the Canadian Pacific Railway (CPR). An important group involved with the planning is shown in Photo 2, including Sir Sandford Fleming, who would survey the railway routes across Canada, including the rugged mountain ranges of British Columbia. Surely this was one of the greatest surveys ever undertaken in civil engineering. This intrepid engineer also became famous as the inventor of the standard time zones of the world.

Early construction experience in rock blasting had been obtained in the open cuts of other short railway alignments constructed in the early to mid-eighteenth century. The Shanly brothers of Montreal, Walter and Francis, participated on some of these projects, then became involved in engineering and contracting on the eastern portions of the ICR alignment. This experience was to serve them well in later years when the opportunity to undertake major tunnelling works arose.

Several short tunnels were necessary for the ICR line. Two examples completed in approximately 1870 are given in the following photos. Photo 3 shows the tunnel at Morrisey Rock, New Brunswick, driven through a rocky bluff. Both the portal excavation and the tunnel are noteworthy for their excellent shaping, and it is difficult to conceive of superior work, even now.

Photo 4, obtained from the National Archives, shows another type of tunnel

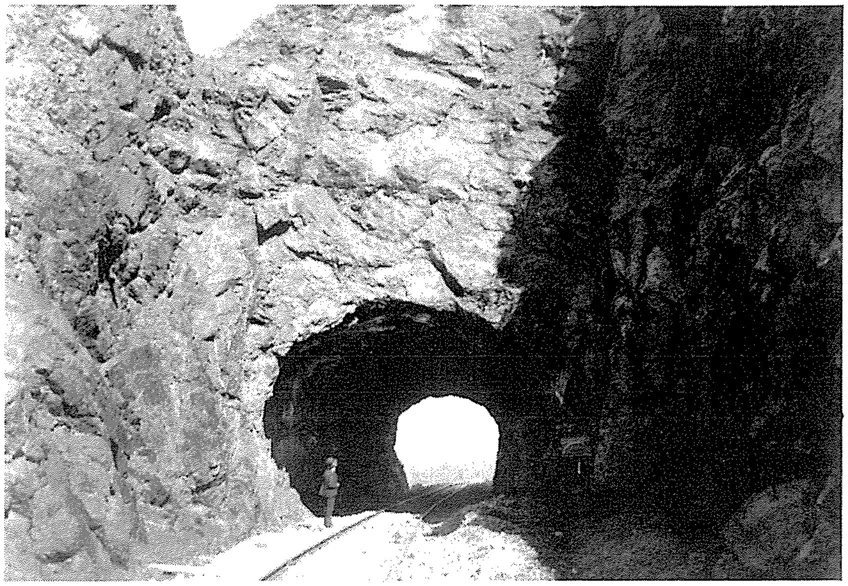

Photo 3. Morrisey Rock Tunnel (Circa 1875, National Archives).

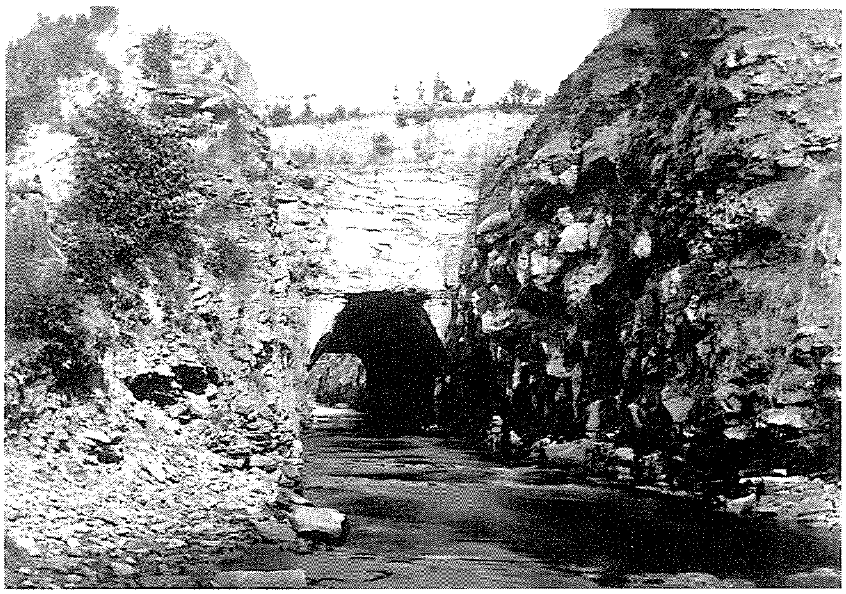

Photo 4. Diversion Tunnel for ICR line (Circa 1875, Location unknown, National Archives).

completed around 1870. The exact location and status is unknown to the author. It is known to be a diversion tunnel, necessary to pass a small river, in order to complete a local grade for the ICR line. Note the squared tunnel roof in what appears to be a sedimentary rock. This shape of tunnel allowed the haunches to provide arch support. Tunnel builders had to utilize the natural strength of the rock to its maximum extent, as artificial support such as rockbolts and shotcrete, was not available.

Although the Hoosac Tunnel is located in Massachusetts, it has contributed greatly to the early expertise developed by early Canadian engineers. The contracting firm owned by Francis Shanly of Montreal was requested to complete construction of this difficult project, where earlier contractors had been unsuccessful. This twin-tracked tunnel is 7,630 m long with two shafts, the central one being 313 m deep. The tunnel was completed Jan. 10, 1875 with several significant advances made in tunnelling technology. One such advance was the refinement of nitroglycerin for controlled blasting, using improved technologies developed by George M. Mowbray, a chemist born in Brighton, England. Mowbray had emigrated to the United States in 1854, where he had applied his knowledge of explosives to increase the output of oil wells at Titusville, Pennsylvania. Shanly encouraged him to investigate and improve the properties of nitroglycerin, rendering it a commercial success, with great practical improvements to rock blasting. A second innovation was the use and improvement of pneumatic rock drills, first patented by Joseph Fowkes on May 9, 1849. The more successful Burleigh drill, incorporating the basic features of the Fowkes drill, was improved and used with great success by the Shanly brothers on the Hoosac Tunnel (Sandström, 1963). Many great improvements in rock drills would be made, principally by American and European inventors and practitioners of the late nineteenth and twentieth centuries. However, they owe their origin to the Fowkes patent, and their early development on the Hoosac tunnels. Subsequently an improved drill, the Rand piston drill, was used to advance the first power tunnel on the Niagara Falls Power House, constructed at the base of Niagara Falls in 1895. Ingersoll-Rand drills, so well know in twentieth-century tunnelling, were a later innovation from two merged companies. Also, the Otis steam elevator for application in use over lifts of 300 m was developed in the central shaft of the Hoosac Tunnel (Walker, 1957).

Construction of the original CPR line across Canada was completed on November 7, 1885, with the last spike driven at Craigellachie, B.C. Intense tunnelling activity was the norm in the five previous years and one report had over 7,000 men engaged in boring 15 tunnels, one of them 1,600 ft long. Sometimes workers had to be suspended by ropes down the perpendicular face of the Fraser Canyon in order to blast a foothold (Ormsby, 1958). These must have been exciting times for tunnelling.

Following completion of the Hoosac Tunnel, the Shanly brothers continued to develop waterworks tunnels in many cities of the east, including both Montreal and Toronto. In addition, Walter Shanly was involved in the initial planning of the transcontinental railway across Canada and the St. Clair Railway Tunnel, a project world famous at the time of completion in 1891. The Grand Trunk Railway, part of the Canadian National Railway's system, to improve shipping along the line from Canada to Chicago initiated the St. Clair Tunnel. The tunnel passes beneath the St. Clair River and connects Sarnia to Port Huron, Michigan. A detailed account of the design and construction of the tunnel is chronicled in the book by Clare Gilbert (1991).

A feasibility study of the tunnel had been completed by Walter Shanly in 1882, prior to Joseph Hobson being hired as chief engineer to complete the project. Hobson, born in Guelph, Ontario, had been involved with major bridge projects, including the International Bridge at Ft. Erie, and had worked with Walter Shanly. The St. Clair project, daring in scope, would be a crowning achievement for Hobson. To succeed, it would be necessary to construct a tunnel in clay, of unprecedented size and difficulty, over 1.5 km in length, only a few metres beneath the bed of the St. Clair River. Open-cut excavations on either side of the river were each approximately one kilometre in length.

Hobson designed two cylindrical shields of 6.58 m in diameter fitted with hydraulic rams for forward thrust. The face was fitted with doors to allow man-entry for removal of the clay. Excavation was by hand spade and shovel and mucking was by mule-drawn wagons. Gilbert shows details of this unique shield in his book. The shield had as precedent the primitive Brunel shield of 1820, and several much smaller shields including the Barlow shield, the Beech shield and a shield being used at that time to drive a tunnel under the Mersey River in England. Hobson utilized these concepts to design a new shield which was by far the largest of it's type to date.

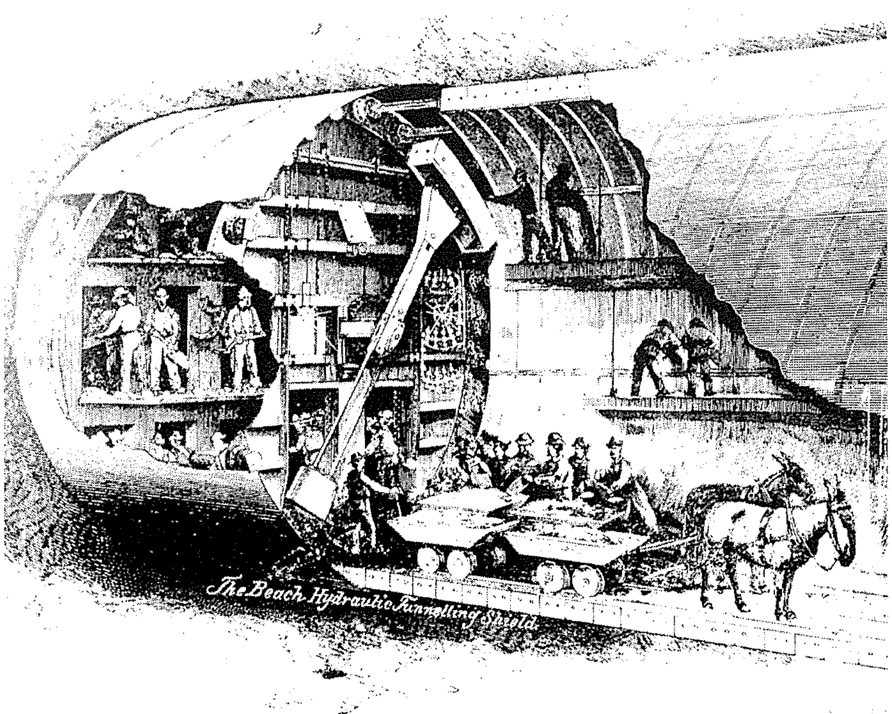

Photo 5. Excavation and Mucking of St. Clair Tunnel (C. Gilbert, St. Clair Tunnel, Rails Beneath the River).

Two Hobson shields were built at the Hamilton Bridge and Tool factory; one to drive the Canadian portion, and one for the American.

The tunnel was lined with bolted cast-iron segments erected by a hydraulic arm. These design features by Hobson were also unprecedented. Compressed air was used to maintain the tunnel face and to control seepage. When the two shields met beneath the St. Clair River the accuracy of joining was within six millimeters. Construction of the largest underwater tunnel in the world had been completed in approximately one year. Photo 5 reproduced from Gilbert's book shows the shield and Photo 6 is the view of the interior of the tunnel.

The tunnel opened to train traffic in 1891 and was superseded only by completion of the new St. Clair Tunnel, another example of fine engineering and construction, but of the twentieth century. Although designated an historic engineering feat by the Canadian Society of Civil Engineers, the St. Clair Tunnel, and it's engineer, Joseph Hobson, are little known to most Canadians. However, in it's day it was world famous, and hosted many foreign visitors interested in the first international underwater link in North America. With completion of the St. Clair project, no major new tunnels were initiated in the nineteenth century. But the twentieth century would bring great new works indeed.

Tunnelling in the Twentieth Century

Railway Tunnels

The first part of the twentieth century continued to be dominated by railways, although the imperatives of the automobile and energy needs for the country also brought major tunnel projects in both transportation and hydroelectric power.

Tunnels for railways now focused in British Columbia to improve the existing CPR line across the Kicking Horse Pass and Rogers Pass, where the surface line was plagued by snow avalanches. To avoid these avalanches and decrease the grade from 4.5% to 2.2% in the descent from the Kicking Horse Pass to Field, B.C., two spiral tunnels were constructed. Completed in 1909, these rock tunnels are famous, mainly for their configuration, and for having provided memorable train journeys for thousands of passengers. Seven years later a third tunnel was constructed to reduce the grade beneath Rogers Pass. The Connaught twin-track tunnel, completed in 1916, was named for the Duke of Connaught, Governor-General of Canada from 1911-1916. It is concrete-lined, just over eight kilometers long, and lies 170 metres below the summit of Rogers Pass. The main ventilation house is at the western portal, and provides forced air for cooling and purging during operation. This tunnel improved not only the grade, but in particular operational safety, providing full service for more than 70 years. It now operates as a single-track line.

The growth of heavy export traffic, including wheat, sulphur and coal, resulted in the development of very heavy diesel-powered unit trains. The decision was made to once again reduce the grade through Rogers Pass. In 1986 construction began on another major improvement, this time with two single-track tunnels some 120 m below the Connaught alignment. The Shaughnessy Tunnel is the shorter of the two at 1.8 km. The MacDonald Tunnel is 14.7 kilometers in length, with a 350-meter-deep ventilation shaft at its midpoint to allow forced-air ventilation. Sliding gates open and close on remote command, controlling the two sections of the tunnel to aid in ventilation. Cooling of the locomotives and purging of diesel fumes is performed sequentially as the train passes through, after which a new train may enter the tunnel.

The tunnel was excavated from both ends simultaneously, the contractors competing in order to arrive first, with the winner being awarded construction of the central section. One contractor used the normal drill-and-blast sequence in full-face excavation. The second contractor excavated the upper portion of the tunnel by tunnel boring machine (TBM) and then blasted the lower section. In this case, the more conventional method won the day, the new TBM having mechanical difficulties in the hard quartzite of the Rocky Mountains. Excavated in the generally excellent metamorphic rock, the tunnel was concrete-lined principally to provide hydraulic efficiency for the ventilation system. Rapid ventilation and quick train passage is the key to the economic benefit of the project.

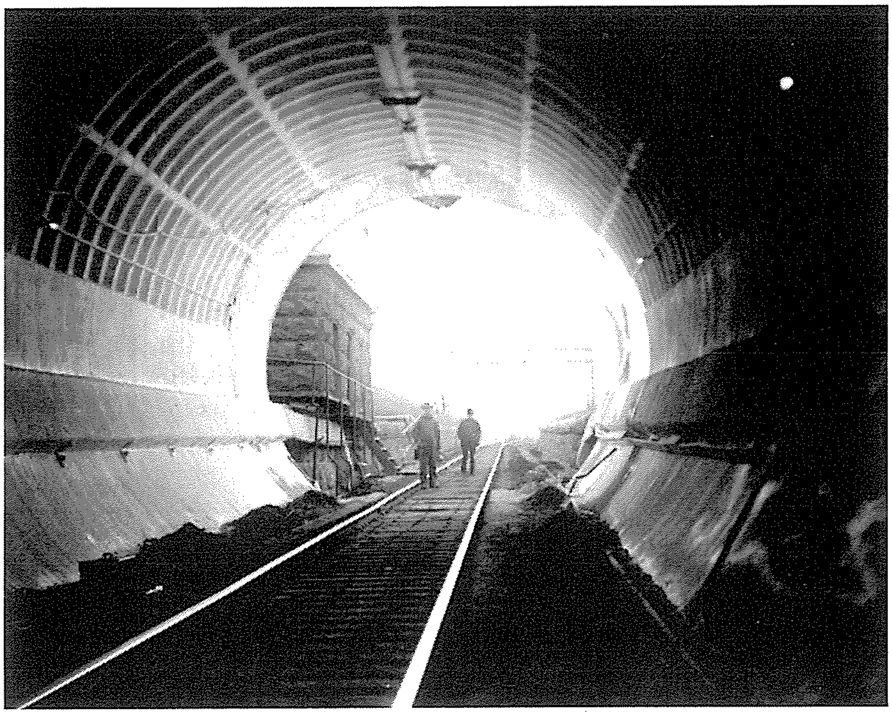

Photo 6. St. Clair Tunnel, Interior View 1908, National Archives.

Prior to completion of the Rogers Pass Tunnel, two other major rock tunnels were completed for B.C. Rail in the early 1980's in British Columbia, northeast of Prince George. Required to provide railway access to the new coal fields of Tumbler Ridge, two tunnels of nine and six kilometers were necessary. Two other short tunnels of 271 and 367 metres were also required along the alignment. All tunnels are inverted-U in shape, 8.5 metres high and 5.5 metres in width. The two long tunnels were initially designed to include forced ventilation, but during construction, a decision was made to use electric trains. Excavated by conventional drill-and-blast with contractors utilizing the Jacob's magic-carpet excavation and mucking system, the tunnels were completed one month ahead of schedule. Pattern rock bolting and shotcrete provide arch support. Special insulation and drainage was installed near the portals of the tunnels to prevent ice formation on the tracks The first shipment of coal from Tumbler Ridge to Japan was made in November 1983.

All tunnels have their surprises and challenges. The Tumbler Ridge tunnels included methane and hydrogen sulfide gas, and rock bursts in highly stressed quartzite. Fortunately, by the late twentieth century, engineers and miners had learned to recognize and deal with these dangerous conditions. "All in a days work" was the way one older miner expressed it. Joseph Hobson would have been impressed, as men were lost due to the effects of such gases in Hobson's time. At Tumbler Ridge new gas warning and ventilation systems prevented such tragedies. Much has been learned in one hundred years of tunnel engineering in Canada.

A number of short tunnels were constructed in the nineteenth century along the original CPR line, especially in British Columbia. Upgrading and line improvement in the twentieth century has increased the number of tunnels to 45 west of Lake Louise. About 40% of these are unlined and none require ventilation. All have been enlarged to allow the passage of double-stack cars. There are also an additional four short tunnels north of Lake Superior; four west of Thunder Bay, and the Wolfe Cove tunnel near Quebec City.

The second great railway system in Canada is the Canadian National Railways, which also has a long history of tunnelling. The majority of these are in B.C., with 29 single-track tunnels

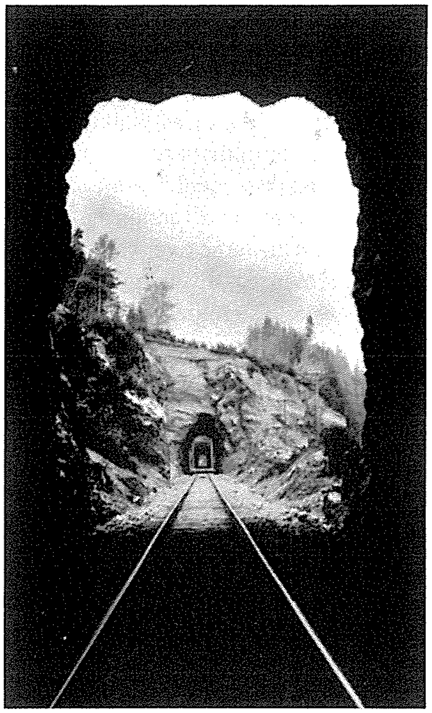

Photo 7. The Three Tunnels at Kitselas Canyon B.C. (*Circa 1914, National Archives*).

through the mountainous Cordillera region, which includes the difficult Thompson and Fraser Canyons. From July 1910 to July 1914 eighteen of the 29 single-track tunnels were constructed, with many of them in these two canyon sections (Photo 7). The remaining 11 tunnels were done for line completion and improvement in later years. The route through the Yellowhead Pass was originally selected by Sir Sandford Fleming, where the grades are modest. Thus, the tunnels required no ventilation.

CN Rail has completed a plan to double track the line, which will require an additional 17 tunnels, up to 5 km in length. Other routes have been investigated, including tunnels up to 27 miles long, which would be far longer than would exist anywhere in the world. The less costly route requiring the 17 tunnels, was selected. To date none of the tunnels have been constructed. Perhaps the next century will see renewed activity in railway tunnelling in B.C.

A unique twin-track railway tunnel, now co-owned by CN and CP railways, was constructed beneath the Detroit River. Completed in July 1910 by the sunken-tube system, it consists of concrete ballasted steel shells, with an internal concrete lining (Kinnear, 1911). Approximately half a century later, CN Rail constructed another unique tunnel in Vancouver, utilizing the new material, "shotcrete," developed in Europe, but used for the first time in North America. Excavated in a weak, friable conglomerate, shotcrete proved to be ideal as the final support. Engineered by the firm of Dolmage, Mason and Stewart, and built by Northern Construction, the use of shotcrete represents another milestone in the development of tunnelling.

The most recent major tunnel completed on the CN line is the new St. Clair Tunnel between Port Huron and Sarnia. The alignment selected was side by side with the original Joseph Hobson Tunnel. Required because trains of the twentieth century could not fit through the original St. Clair Tunnel, the new tunnel is about 50% larger. Driven through clay by a Lovat TBM manufactured in Toronto, and lined with concrete segments, it was completed in 1993. Winner of the Governor-General Award for Engineering, the tunnel is a credit to the designers and builders, showcasing Canadian tunnel engineering one century after Hobson's great work (Hatch Mott-MacDonald, 1996).

Transportation Tunnels

Three types of transportation tunnels now exist in Canada, having been developed over the last 60 years. Firstly, concrete-lined 2-lane highway tunnels built mainly in British Columbia; secondly, sunken-tube concrete tunnels constructed on the bottom of major rivers; and, thirdly, rail tunnels for rapid-transit systems in Toronto, Montreal, Vancouver, Edmonton and Calgary.

The first automobile tunnel was built between Detroit and Windsor in the 1930s, and has been in continuous service ever since. Designed by Parsons, Klapp, Brinkerhoff and Douglas, this sunken-tube tunnel is about 1.5 km in length, with 2 traffic lanes (Thorsen, 1930). The original ventilation system, maintained and upgraded, still works well. The Louis-Hippolyte Lafontaine Tunnel, was built in the 1960s crossing the St. Lawrence River at Montreal. This is a major six-lane sunken-tube tunnel with a total length 1,390 m, including a central river section of 730 m. (Brett and Oulette, Lalonde and Valois, Per Hall and Associates, Bulletin, 1965) The George Massey Tunnel, completed in 1962, is a 4-lane sunken tube, 1.5 km in length, crossing the south arm of the Fraser River near Vancouver (Fenco, Christiani and Nielson of Canada Ltd.) Finally, two tunnels were built in the 1960s and early 1970s in southern Ontario, the Thorold and Welland Tunnels beneath the Welland Canal. Engineered by H.G. Acres and Co. Ltd., these tunnels were constructed in the dry by crossing the Welland Canal in the winter construction season. All these tunnel projects involved Canadian engineers and builders, with some of the companies in joint venture with foreign firms. The Thorold Tunnel entrance shown in Photo 9 displays the classical aspects of such tunnels, truly beautiful civil engineering structures.

Rapid Transit Tunnels

Underground rapid-transit systems in Canada are relatively new. Construction of the first one, in Toronto, began in 1949, using cut and cover techniques in glacial soils, although the southern 300 m was in the Dundas shale (Leggett, 1960). Extensions to the first 5-mile section along Yonge St. then utilized tunnelling methods with machine and hand excavation, and fully lagged rib-supported tunnels. Both cast-in-place concrete and segmented, gasketed concrete liners were utilized successfully. Several extensions to the system were constructed in later years. The planned extensions along the Sheppard and Eglinton West routes are designed to utilize TBM's manufactured by Lovat of Toronto. Two machines have been built with slurry face capability, and await the start of construction. These modern machines are a testament to the capability of one of the world's premiere tunnelling companies, which began operation in the 1950s in Toronto. First developing small machines of about 2 metres diameter for excavation in weak saturated soils, Lovat now ranks with the top companies of the world, with capability to deliver TBM's for soft ground excavation up to 14 meters in diameter.

The twin-tunnel portion of the Edmonton rapid-transit system is 600 metres in length, also constructed in glacial soils. Difficult soil conditions necessitated the use of a slurry face TBM, with special support required to control running sands ahead of the face. These techniques, imported from Europe, represented the first use of a slurry-face TBM in Canada. In addition, the Sequential Excavation Method (SEM) developed by Professor Z. Eisenstein was first used on this project (Phelps, 1989).

Two other rapid-transit systems, in Vancouver and Montreal, were constructed in rock using conventional drill-and-blast excavation, with cast-in-place concrete linings. For the Vancouver tunnel, an original railway tunnel used to deliver mail from the harbour to the downtown post office, was increased in height to accommodate an over-and-under rail system.

No doubt each of the existing rapid-transit systems will be extended by future growth, and new ones begun in other Canadian cities. The techniques for both design and construction will have the advantages of world technology, and Canadian engineers fully capable of completing the work.

Hydroelectric Tunnels

The major tunnelling activity of the mid-century was associated with the development of water power. Hydroelectric projects often require tunnels for river diversion, or to supply water to the powerhouse. When the powerhouse is underground, tunnels are necessary for the headrace and tailrace, and for various accesses. The headrace tunnels are often required to operate under high internal pressure, and may be either concrete lined or unlined, depending on the rock conditions. The design life of such facilities is typically 100 years.

Almost all tunnels for power projects are in rock, although short sections of soft ground tunnels are sometimes necessary. The design of these tunnels, and the underground powerhouses, requires the combined efforts of geologists, engineers of almost all disciplines, and contractors. These capabilities have been fully developed in Canada, with engineering companies known internationally for the design and construction of some of the world's largest hydroelectric projects.

One of the first power tunnels was the Bridge River Tunnel completed in 1930 for the B.C. Electric Company, located 175 km northwest of Vancouver. About 4 km long it passes through Mission Mountain 730 m beneath the summit. Dealing with the high stresses induced by the overlying rock mass, and penetrating water-bearing faults, as encountered on this project, provides a great sense of accomplishment for tunnellers. Dozens of projects of this nature were to follow, especially in the mountainous regions of Quebec, Labrador and British Columbia, providing Canadians with the power necessary for everyday needs and for the country's industrial requirements. As well, export of a portion of the power to the U.S. has helped increase the size of these projects. The great rivers of Canada, when developed to utilize the total available energy, resulted in huge projects like the Sir Adam Beck powerplants built on the Niagara River, where 14-meter-diameter tunnels were excavated in the 1950s through the highly stressed caprock of the Niagara Peninsula. Valuable lessons in rock mechanics learned here would advance the science of tunnel building. Since the 1950s, in British Columbia, great projects such as Portage Mountain, Mica, Revelstoke and others required world-ranked dams, but equally, major tunnelling works for river diversion and power facilities. In the large river valleys of the Prairie Provinces, diversion and power tunnels were also required, but in much weaker rock. On the Gardiner Dam, completed in the 1960s, five 6-meter-diameter tunnels were constructed using a TBM, the first use in Canada of this size.

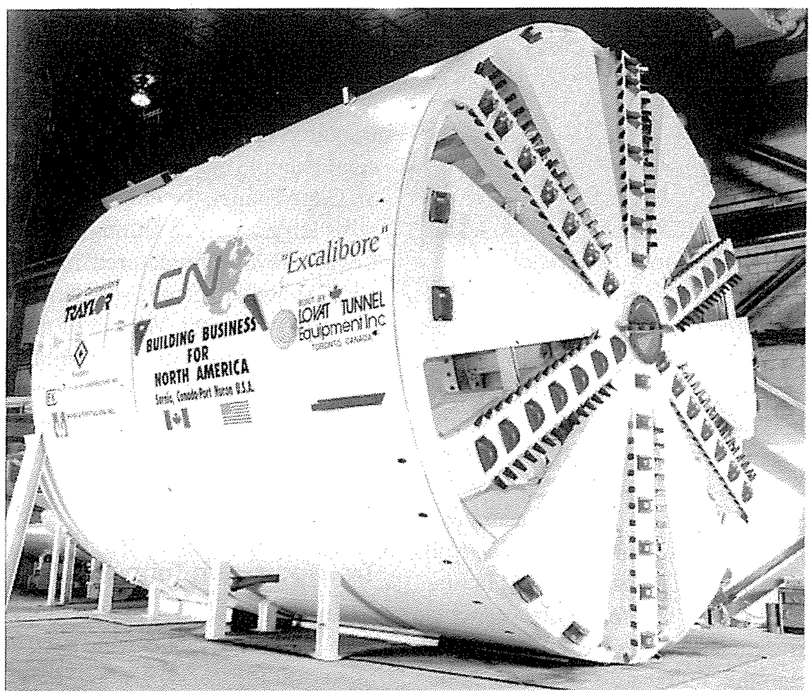

Photo 8. Lovat TBM used to drive new St. Clair Tunnel.

The La Grande power complex owned by Quebec Hydro, and the Churchill Falls project owned by Newfoundland and Labrador Hydro, are world-scale projects where rock tunnels and underground powerhouses are the norm.

Containment of high-pressure water within power tunnels is essential. The tunnel must be located to ensure that the rock stresses exceed the internal water pressure, or that impervious steel liners safely carry the water to the turbines. Canadian engineers have optimized such designs on some of the largest projects and longest tunnels in the world. Now almost a standard design approach world wide, projects such as Bersimis I and II, Chute-des-Passe and Kemano may be cited as examples of well optimized early designs. In 1953 the 16 km long Kemano Tunnel conveyed water to one of the world's highest-head powerhouses, with a water pressure head on the turbines of almost 900 metres.

Since construction of the first underground powerhouse at Kemano, numerous others have been built. Among these are the two largest in the world, Churchill Falls and LG - 2. Typically 25 m wide and 45 m high and more than the length of three football fields, the major cavities are immense. (Cousineau, 1990). Their arched roofs and walls are supported only by rock bolts and reinforced shotcrete. Numerous pillars, intersections and transverse tunnels, created by lateral galleries and water passages, make these cavities awe-inspiring indeed. Canadian engineers have created these designs and exported the technology to many countries through the efforts of engineering companies and individual consulting engineers.

Special Interest Tunnels

Due to the ability to utilize the underground in three dimensions, special interests can be served. These may be military, as in the case of the NORAD facilities near North Bay, Ontario, or the tunnels created by the Third Tunnelling Company, Canadian Engineers during World War I (Schutzer, 1967). Or they may be for such diverse civil engineering purposes as the following.

Tunnels of Little Chicago

Beneath Moose Jaw, during the early part of the twentieth century, a number of tunnels were built for extraordinary purposes. Largely unknown to the Canadian public they are now becoming a tourist attraction. They were created to either house illegal immigrants, or more likely, to provide safety for Chinese workers brought to Canada to help build the railway. Apparently the tunnels were utilized during the roaring twenties for certain illegal activities in Moose Jaw, known then as "Little Chicago" for it's lawless ways (Tunnels of Little Chicago, 1996). The engineering aspects of these tunnels have not yet received attention, but deserve study.

Niagara Falls Tunnels

To see and feel the effect of Niagara Falls, simply take the elevator and walk behind the falls in a tunnel constructed in 1944 exactly for that purpose. An example of utilizing the third dimension for engineering and social purposes, the tunnel has been visited by countless tourists. Excavated by drill and blast, lateral concrete-lined galleries provide access directly behind the curtain of falling water. This tunnel system superceded an earlier one constructed for the same purpose in the 1890s.

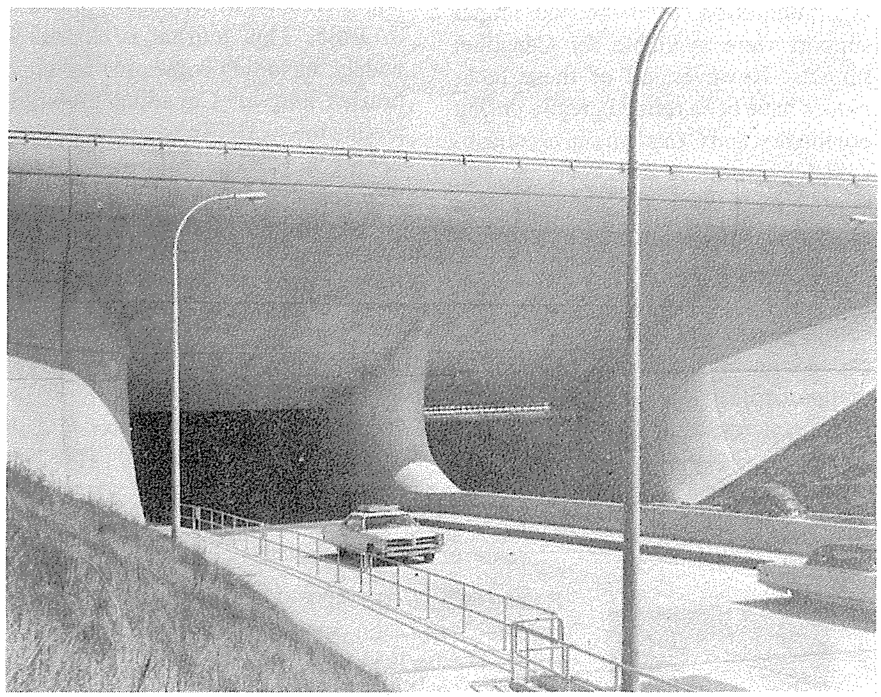

Photo 9. Entrance to Thorold Tunnel (From the H.G. Acres Thorold Tunnel Bulletin, Sept. 1968).

Ripple Rock Tunnel

In the middle of Seymour Narrows, 80 km northeast of Vancouver, Ripple Rock was a hidden menace barely submerged in the shipping channel. From the 1800s until it was removed by blasting in 1958 it claimed 120 ships and 114 mariners. After exhausting a number of overwater attempts, a tunnel 720 m long was driven, accessed by a shaft from the shore. (Patterson, 1966). Two 90 m raises directly into Ripple Rock provided construction access for a number of small lateral drifts; 1,375 tons of Nitramex were packed into these drifts. Detonated on April 5, 1958 as the largest non-atomic blast ever, 370,000 tons of rock were removed in a single blast. Ripple Rock was reduced by 14 m to provide a safe shipping channel. Another creative tunnelling solution.

AECL Research Laboratory

Canada's Underground Research Laboratory (URL) was constructed near Pinawa, Manitoba, to evaluate the concept of disposing of high-level nuclear waste in the stable plutonic rocks of the Canadian Shield. It includes a 2.6 metre circular shaft to 464 metres deep with two levels of tunnels for research activities. Skilled personnel study the geology, geochemistry, hydrology and geomechanical behavior of the rock mass. Sophisticated instrumentation is utilized to determine rock behavior. New methods of full-face shaft sinking were employed, and special blast designs and explosives were utilized for controlled perimeter blasting to create precise cavities. The knowledge gained in rock behavior and excavation has also been applied to conventional mining and civil tunnelling.

The Future

Modern tunnellers have had the advantages of the experience and knowledge built up over at least 15,000 years, as underground stone-age mines of this age have been discovered in Europe. Over this period, herculean efforts and great sacrifices, paid with the lives of uncounted workers and slaves, paved the way for modern tunnellers. It is instructive, in some ways mandatory, to read the great book of G.E. Sandström published in 1963 on the history of tunnelling. One realizes that at least rudimentary technologies of drilling, blasting, ventilation, drainage and tunnel support were available for Canadian tunnels. However, all of these techniques have been refined greatly during our history, and Canadians have contributed fairly, both in hard rock and soft ground tunnelling. Tunnelling is now taught in universities as a primary course. Engineering companies specialize in the design of tunnels. Canadian companies manufacture TBM's, drills, excavation and mucking equipment, pumps, explosives, rockbolts, shotcrete, grout, concrete segments and other materials necessary for tunnelling. The whole integrated array of services is available within the tunnelling fraternity in Canada. Skilled workers are available to do the actual construction, and the history of one dedicated group of British Columbia tunnellers is discussed in the book by Warrior and Leier, 1992.

The Tunnelling Association of Canada (TAC) was founded in 1979 to provide a central voice and perspective for all persons interested in tunnelling. This national body represents Canada at the International Tunnelling Association, and has chapters in centers of tunnelling activity across the country. The annual journal of TAC is the *Canadian Tunnelling Canadien*, which began publication in 1985. This journal is distributed widely, including copies for various libraries and all Canadian embassies around the world. To be updated on tunnelling in Canada requires one simple step, membership in the Tunnelling Association of Canada – all are welcome.

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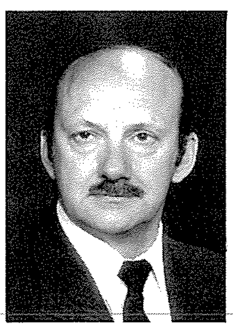


RAYMOND P. BENSON, born in Saskatchewan, received his civil engineering degree from the University of Alberta in 1960. Subsequently he studied soil mechanics at the University of Illinois, where he took a Ph.D. in rock mechanics under Professor Don U. Deere.

He worked for the Prairie Farm Rehabilitation Administration, International Power and Engineering Consultants on the W.A.C. Bennett Dam, and Acres Consulting Services. From 1976-93 Benson held the offices of vice-president engineering, then president of Klohn Leonoff. Currently, he is senior vice-president and chief engineering officer of Klohn-Crippen Consultants. He has consulted on numerous tunnel, dam, hydroelectric, water resource, and transportation projects at home and abroad.

Dr. Benson has worked and chaired many technical committees and conferences, is a past president of the Tunnelling Association of Canada, and in 1993-94 was president of the Engineering Institute of Canada. He has served on the advisory board of Kwantlen College and the British Columbia Institute of Technology.

The Development of Geotechnical Aspects of Permafrost Engineering in Canada: Observations and Recollections

Ed McRoberts

The destructive action of permafrost phenomena has materially impeded the colonization and development of extensive and potentially rich areas of the north. Roads, railroads, bridges, houses, and factories have suffered deformation, at times beyond repair, because the behaviour of frozen ground was little if at all understood. In consequence the structures were built without the proper protective features that would enable them to withstand the subsequent heaving, settling and other effects of frost action."

From Siemon Muller (1943) in Permafrost or Permanently Frozen Ground and Engineering Related Problems

My first experiences with permafrost and other unique aspects of Northern Engineering were as a high school student in the Yukon. It is fair to say that permafrost was a household word. During those years I grew up with stories about construction of the Alcan later Alaska Highway and the Canol Pipeline from Norman Wells to Whitehorse. I visited Dawson City on several occasions and learned first hand the apparently oxymoronic character of the word permafrost, given its evident impermance and propensity to thaw out creating awesome settlement of buildings, disappearing roads and so on. I also worked on a small placer gold mine and saw my share of exposed ice formations long before I read about it in books. Perhaps my most formative experience had to do with summer trips into the bush where it was possible to find a supply of cold storage for certain forms of liquid refreshments.

The sporadic and discontinuous nature of the permafrost became apparent. It also seemed that strong clues were offered by vegetation. There was no point digging in pine woods, but slightly raised bits of boggy ground offered possibilities, assuming you either didn't mind getting wet or had high boots on.

My early practical experience was rounded off with two summers spent working on the Alcan Highway as it was still called, which at that time was operated by the Canadian Army. The importance of lines of supply and communication in the North were first learned on a bridge job north of Kluane Lake.

I spent a summer working as a labourer on a new bridge requiring long steel girders. These were shipped from Japan to Skagway in Alaska and then by rail to Whitehorse and by the Alcan highway to site. As the girders were being lowered into place, it became apparent that they were either one foot short, or the bridge seats were one foot too far apart. This resulted in a full year delay for the bridge and the unhappy circumstance of prematurely losing my first good summer job. I suspect this experience also had something to do with a lifetime's attention to detail with metric conversion.

The Early Years up to WW II

In Canada prior to WW II technical interest in permafrost seems almost nonexistent and there are few references made to it in technical literature. The first commercial application of permafrost, according to Brown (1970), was probably made by whalers operating on the Arctic Ocean who used chambers in the ground for cold storage.

The mid-1920s saw the first development of oil reserves at Norman Wells, and by 1929 a railway through permafrost terrain reached Churchill, Manitoba. In the thirties gold mining began on Great Slave Lake and the Eldorado uranium mine was in operation on Great Bear Lake.

Apart from these projects, and the formative experiences of Farley Mowat, not much was happening in the Canadian north.

The Military Connection to the Development of Canadian Permafrost Knowledge

The early years of Canadian permafrost development were driven first by WW II and then by the cold war.

There were some big projects during these war years, such as the Alcan Highway, the Canol Pipeline for the defence of North America, and the Northwest Staging and Crimson Routes, which provided airborne major supply lines to the Soviet Union. The northern parts of Canada and Alaska were now strategic places. But it had become apparent through a process of trial and error that construction techniques and designs that worked elsewhere weren't going to work in the North. What were needed were engineers experienced in permafrost and there were few, if any.

After WW II the concern now became the potential for aeroplanes from

J.F.Nixon

N.R.Morgenstern

Ed McRoberts

Permafrost exploration - Jet boating on the Mackenzie River 1972.

the opposite direction, and with different intent. Even larger and more reliable airfields were now required. Construction of the Distant Early Warning or DEW line of radar stations was also under way. Substantial funding was available and even Ottawa began to kick-in with major efforts, as summarized by Brown (1970), being commenced in the early 1950s.

My own interest in the north and in engineering had got a big boost from that army bridge job in 1964. I was so impressed by all the brass that showed up in big staff cars to find out what had gone wrong that I decided the life of an army engineer was for me. While it was subsequently proven to my satisfaction that the army part of this equation was not, I joined the Corps of Royal Canadian Engineers as an Officer Cadet. I ended up at the University of Alberta, where in those days the word permafrost certainly appeared in the courses, and the staff such as Dean Hardy and Stan Thomson had worked in the North.

This personal army connection led me to being posted to the Royal Military College for the summer of 1967, en route to Imperial College for post-graduate work. My summer research assignment was exceedingly boring, but the RMC library saved me. I believe the chief librarian at that time had an interest in the North and in any event there was an eclectic collection of northern related information. Many of these books ended up on my research desk, which gave me a more formal introduction to the subject, and a good understanding of how it had developed.

The RMC library had the closest thing to a textbook on permafrost in 1967: the short book called *Permafrost* first compiled in 1943 by Siemon Muller. This book represents the beginning of permafrost engineering in North America. It was genesis; it was the permafrost equivalent of Terzaghi's *Erdbaumechanik.* My copy of this book tells me it was first published under the name *Strategic Studies No. 62* in 1943 by the Military Intelligence Division of the US Army.

...a high level of Russian self-interest in order to ensure a year round and reliable supply of aeroplanes, led to a considerable degree of glasnost.

As can be deduced from the introduction to Muller's book, military endeavours during the early part of the war to build up an infrastructure, had run into considerable difficulties in permafrost country. Information was needed. Much came from the Soviets who at that time were far ahead of North America in engineering applications in permafrost. Muller's book drew heavily on Soviet references, and also appears to have been the vehicle by which many Russian terms found their way directly into English language permafrost usage. Exactly how all this Russian information was obtained is not made clear. I would speculate that a high level of Russian self-interest in order to ensure a year round and reliable supply of aeroplanes, led to a considerable degree of glasnost. It is also interesting that out of a comprehensive bibliography of some 80 citations, about 60 were translated from the Russian and about 20 were in the English language, with only one identifiable as being Canadian. This one Canadian reference was a book on ice engineering by Barnes (1928) published in Montreal.

Muller's compilation as far as I know first introduced the term "permafrost" as shorthand for "permanently frozen ground." By this we mean any organic terrain, soil, or bedrock that exists in a continually frozen state. Muller's work comprehensively defined the major topics in geotechnical engineering aspects of permafrost that we now understand to be as follows:

Distribution. How do you find permafrost, where is it [both vertically and horizontally] and as importantly: where might it not be?

Type. What kinds of permafrost are there, how ice rich is it and where did the ice come from, or how was it formed?

Ground water. What flow regimes exist in the unfrozen zones or taliks that can be found?

Thawing. What happens when permafrost thaws?

Freezing. What happens to unfrozen soil when it freezes?

Frozen. What are the properties of permafrost in its natural state, how much load can it carry?

While we have made great progress in the fifty-four years since these topics were introduced by Muller, they still remain the focus of geotechnically related northern engineering research.

I also recall in 1967 reading Muller's introduction, and I quote:

"Judging from the similarity of conditions in Siberia and Alaska it should not come as a surprise if the newly built Alcan highway suffers certain damage causing delays and even disruption of traffic. The most destructive swelling of the ground and heaving of structures usually occur in the winter and are followed by equally destructive settling, caving and sloughing of the ground during the summer thaw. Unfortunately... no systematic observations on frozen ground phenomena were made...[and]... had they been made would have been of immeasurable value in making the repairs of the damage that is likely to occur..."

Some twenty years later when I worked on the highway, repairs were still being made. This personal observation made as a young graduate led me to thinking that permafrost work offered a future career prospect.

I also recall that an important reference in the RMC library was the First International Permafrost Conference. This had been held in Purdue just after Volume 1, Number 1 of the *Canadian Geotechnical Journal* was first published in September 1963. Of the some 40 Canadians who went to this conference and worked in the North, I was later lucky to meet and work with many. There were approximately 100 papers in this conference, 22 of which were from Canada. Of the 51 delegates who served on nine panels, 12 were Canadians. We had finally made our international mark in the subject. And just in case the reader

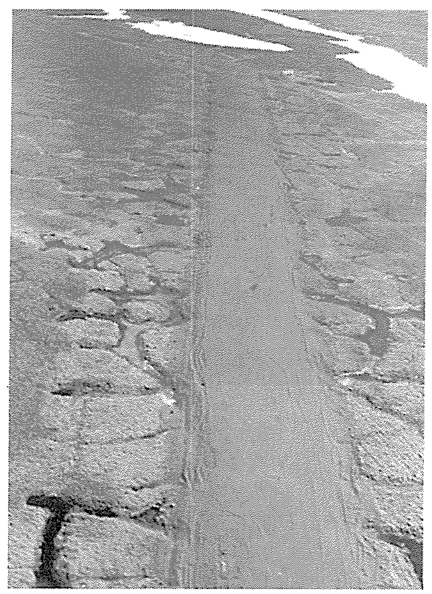
Trials of ditching in permafrost for buried pipelines backfilled with excavated spoil which subsequently thawed out.

feels I am exaggerating the military application, the guest speaker at the dinner for the Purdue conference was a US Army Lieutenant- General.

I returned to the RMC library in the winter of 1970/71 having been posted to RMC, this time as an Assistant Professor teaching highway engineering. By now pride of place in the library was given to Roger Brown's book *Permafrost in Canada* which was, as I recall, hot off the press. In those days the bulk of available permafrost information tended to be from American sources, and a home-grown Canadian effort was welcome.

The main incentive for the tremendous American effort was of course primarily due to the military requirements for northern air bases, roads and so on, particularly in Alaska, and as well, ice- related work in Greenland. I also suspect that Americans seeing that the Soviets had more actual permafrost than they did, were not about to concede supremacy. Whatever the reason, the work coming out of the US CREEL in Hanover, and the USGS in Menlo Park, benefited many Canadians. And then there were a few Russian translations, some of which were of considerable interest.

Prior to Roger Brown's book in 1970, the greater part of Canadian information, as I recall, came from the many publications of the Division of Building Research, NRC, with the Canadian Permafrost as well as Muskeg Research Conferences being important reference material. A notable exception was, I believe, the only early Canadian textbook on soil mechanics [of itself a considerable novelty.] This 1966 book *Introduction to Soil Behaviour* by Yong and

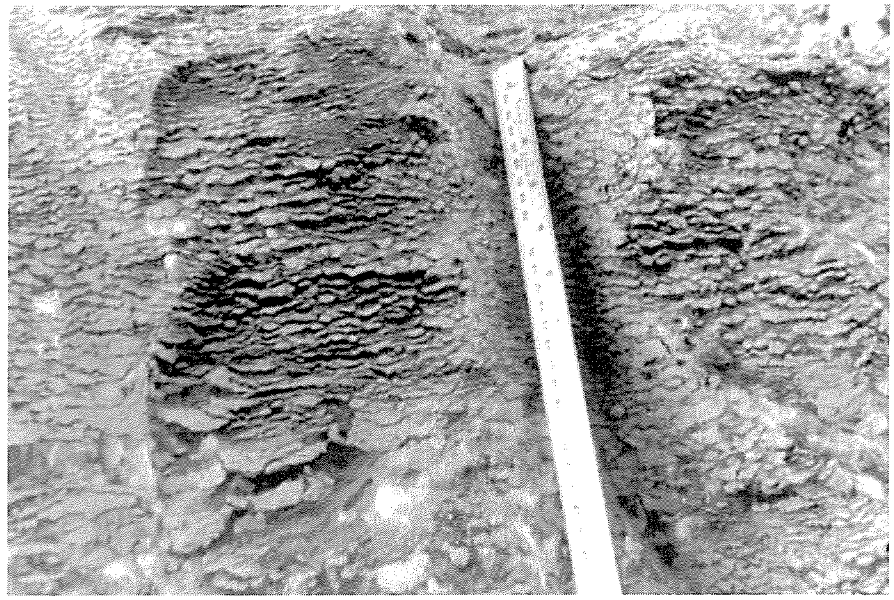


Runway built over permafrost along Arctic north slope showing ice wedge polygons and thaw settlement of ice wedges reflected in fill.

Warkentin, had a full chapter on soil freezing and permafrost. Another noteworthy Canadian contribution from this era was Hamelin and Cook's (1967) book that provided an illustrated glossary of periglacial phenomena. While directed to a geographical focus, this work provided an excellent summary of the many unique features and natural processes at work in the North. As engineers, these processes were things we had to mechanistically quantify.

Much if not all of the early Canadian work was directed, first, by the Associate Committee on Soil and Snow Mechanics, and then the Permafrost Subcommittee of the Associate Committee on Geotechnical Research of the National Research Council (with other subcommittees on Snow and Ice, Soil Mechanics, and Muskeg.) The origin of these committees goes back to the war years, with the Permafrost Subcommittee begun in 1960. Roger Brown's book provides a comprehensive history of the development of Canadian permafrost experience in the period from Muller's book up to the end of the sixties. His book traces the important work undertaken both by him and his co-workers at the Division of Building Research of the National Research Council. This work began with a survey of building foundations down the Mackenzie River valley by John Philainen in 1950.

Brown's book and its publication also tend to mark the end of an era. This book however was meant as a geographical summary of the North; it was not an engineering text.



Close up is of ice distribution causing thermokarsting.

Large thaw-induced retrogressive thaw flow slide in glaciolacustrine permafrost in Mackenzie River Valley.

The Northern Pipeline Studies Boom Years

The oil discoveries in Prudhoe Bay in Alaska began the next phase. In Canada this transition was marked by two events. First, the third Canadian Conference on Permafrost held in Calgary in 1969, which some 400 Canadian and US people attended. With a theme of permafrost problems related to mining and oil and gas industries, this conference marked a new major focus of interest in the North. Second, in December 1968 the Canadian government set up a multi-department Task Force on Northern Oil Development.

This next phase of northern work was a frenetic rush to develop a secure northern supply of oil and gas, driven by Middle East instability and rising oil prices. Major pipelines were being proposed, from both the Alaskan North Slope and from around Inuvik in the Mackenzie River Delta. Many of these proposed oil and gas pipelines ran through Canada and were obviously going to have to cross permafrost as well as major and minor rivers.

The basic literature on the subject at that time could easily be put on a small set of shelves. It was obvious that our knowledge base was deficient, and basic research was needed.

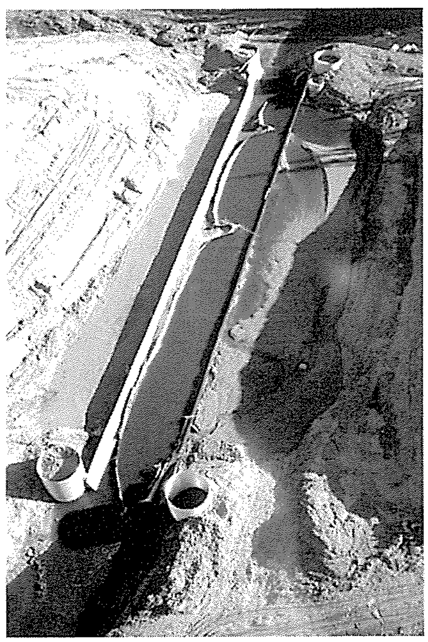
By 1971 I had resigned from her Majesty's service and had returned to the University of Alberta to work on a permafrost subject under Nordie Morgenstern. I had with luck landed into a topical and wide-open field for research. About 5 months after I started on my own research, I attended a NRC-sponsored conference in Ottawa in February 1972 on Canadian Northern Pipeline Research. Apart from the pleasure of making my first written contribution to the literature, it was my first opportunity to put faces to the many pioneers in the field.

Task forces were popular in those days and an address at this conference by the president of the Treasury Board-C.M. Drury-described the Task Force on Northern Development with five subcommittees: Pipelines, Economic Impact, Marketing, Marine Transport, and Environmental-Social that had begun in December 1968. I didn't appreciate it at the time, and no doubt no one else did either, given the tremendous funding from pipeline companies, but this Environmental-Social committee—and what it spawned in such things as the Berger Hearings—was later seen by many as the kiss of death for many of the big visions of the time. It is also fair to say that falling oil and gas prices and the risk associated with the technological challenges of operating large-diameter gas pipelines underground also had their effect.

My research proceeded to the planning for an intensive field season on research on permafrost slope stability. Funding had been obtained from the Canadian Geological Survey which would allow for about 10 days of Bell helicopter time in the Mackenzie Valley. Having already seen the valley by air in a first reconnaissance from Inuvik to Fort Simpson, and having looked at what seemed to be every set of photographs in the Ottawa air photo library during my trip to the pipeline conference, I concluded there would be few places to land a helicopter. A boat was the answer, and through advice from Stew Sinclair, the Civil Department Chair at the time, I found a jet boat. Insurance was needed and we finally found some direct with Lloyds of London. This insurance took up a full 1/3 of my entire budget, which gave me the odd twinge of concern. I also needed crew and was lucky to get two fellow permafrost students, Derick Nixon and Bill Roggensack, talked into coming along. Nordie also served as crew and I am not sure to this day if he appreciates we almost drowned in the Sans Sault rapids. Lloyds however never had to pay out.

Back at the U of A, I was classmate with several people, all of whom have made significant contributions to the field and who remain active in northern engineering. I was also fortunate to have Ross Mackay as my external examiner on my slope stability work. I had however done some work on quantifying expulsion of water from a freezing front, and as this was of interest to pingo formation, I recall managing to devote the entire examination to pingos.

I left U of A in the fall of 73 and got a job with R.M. Hardy and Associates, seconded as Geotechnical Manager at Northern Engineering Services Company Limited. This company did all the technical work for one of the big proposed gas pipelines. This was an exceedingly interesting assignment, and a real side benefit was the opportunity to meet many high-profile research workers and consultants. I managed two trips to USCREEL and met many of the earlier workers there who had made such major contributions to our knowledge. I also recall a meeting with Arthur Lachenbruch of the United States Geological Survey in Menlo Park whom, legend has it, more-or-less singlehandedly stopped the early buried version of Alyeska pipeline in its below-ground tracks. Several of us visited his home, and I recall Derick Nixon who was also at NESCL and me being exceedingly impressed with his personal library which included both editions of Carslaw and Jeager and fast numerical solutions; this book was a must for most geothermal analysis.



Winter fill placement of granular soils and subsequent thaw led to collapse of large diameter culvert.

The boom years ended with a bust, sometime around 1978. The economic incentives of rapidly rising Middle East crude prices were gone, and the Berger Hearings had placed a moratorium on development down the critical Mackenzie Valley corridor. Attention then focused on possibilities down the Alaska Highway, but by 1982 or so mega-projects were dead.

There had been a lot of studies, several Arctic pipeline research stations built in Canada, but no big project was undertaken in Canada. However much useful design and construction data was obtained as several major test facilities that installed representative lengths of both buried and above ground oil as well as gas lines. These facilities simulated both thawing conditions in oil lines as well as frost heaving in chilled gas lines.

For Canadian permafrost engineers there had been an enormous increase in the knowledge base and of the availability of trained engineers, that was subsequently put to good use. The permafrost community owes a lot to the oil and gas industry who recognized knowledge gaps existed. Being sophisticated users of technology, this industry understood the payoffs that would and did accrue with well-funded research.

Rational Development

While all the effort of the pipeline boom years in Canada did not result in a northern mega-project, a rich literature was developed. In 1978 the first true textbook on geotechnical engineering of permafrost was published by Andersland and Anderson (1978.) As a reviewer at the time commented: "The

Horizontal coring program to obtain undisturbed samples of ice rich soil for studies of lateral loading interactions of creep in buried pipelines.

Rear of aircraft hanger built in discontinuous permafrost zone with differential thaw settlement visible along window line.

tone of this book is distinctly mechanistic, a welcome counter to the flood of purely descriptive cold regions literature." This book was followed in the same vein by Johnson (1981) and more recently by Anderson and Ladanyi (1994.)

Canadian engineers have made important contributions both as authors and in providing the extensive reference materials found in these books. These texts, and the reference material in them, go a long way to answering the questions posed earlier.

For example, the general distribution of permafrost is now well-understood and identifiable by aerial photographic interpretation and in particular by vegetation. Geophysical techniques, exploiting the resistivity difference between water and ice, can be used to map sporadic or discontinuous permafrost.

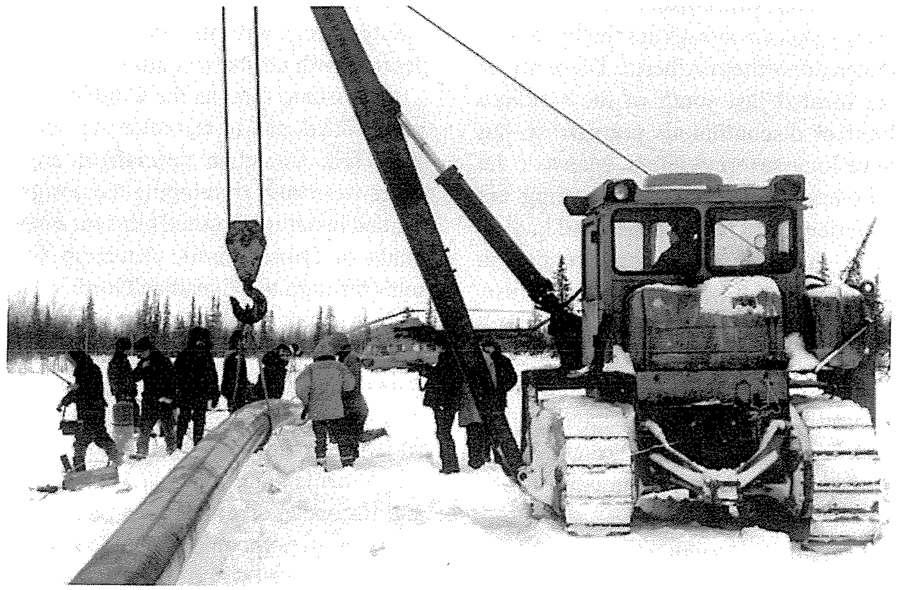
When ice-rich ground thaws, thermo-karst results. If thaw proceeds faster than water can seep out of the soil water pressures in the soil exceeding the hydrostatic condition are generated, weakening the soil. This process called thaw-consolidation has been quantified and provides a mechanistic explanation for the loss of strength encountered in thawing ground and explains such phenomena as solifluction—the movement of thawing permafrost slopes on exceedingly shallow gradients.

When unfrozen ground freezes, insitu water expands but, more importantly, the interaction of ice with the small pores in fine-grained soils creates suctions, which under certain conditions sucks available water up to the freezing fringe and creating an increase in water content and ice lensing. Significant developments in understanding frost heave have been made with the ability to now make sound estimates of heaving when saturated ground is frozen. However, a fully rational method of determining frost-jacking loads for pile or post foundations, remains to be discovered.

Because permafrost contains ice, and because ice can creep, the strength and deformation properties, especially of ice-rich ground, are time-dependent. The same permafrost, which is difficult to excavate especially in the winter, will present difficulties in the long-term support of heavily loaded foundations, even if the ground is kept frozen. Methods for the prediction of deformations of frozen ground under load are well advanced. Studies of the creep deformation of natural permafrost slopes have been undertaken.

Types of permafrost are now well understood with, for example, issues to do with saline permafrost—which were a surprise to those not familiar with the Soviet Construction Standards and Regulations or "SNiP's"—have been rediscovered and quantified. Saline permafrost comes about, for example, where old pre-isostatic rebound marine sediments are thrust above the land and frozen. Salt concentrations of even greater than seawater can be encountered as the freezing process redistributes salts. These salts depress the freezing point, with the result that permafrost well below zero centigrade can act just like a normal soft south-of-sixty unfrozen soil.

The last 20 years have seen a slow but steady development of northern projects in mining and petroleum. Eventually a pipeline was built down the Mackenzie River Valley from Norman Wells to Zama in northern Alberta. This was a smaller-diameter oil line, and because of the peculiarities of Norman Wells, crude could be pumped at temperatures near freezing. Therefore a buried pipeline was technically viable. It was not accidental that much of the pipeline route in permafrost terrain was located on the already disturbed segments of a winter road used to build and maintain an overland pole-supported telegraph cable, the CNT, line from a generation before. Another technological development, more in harmony with nature, was the use of woodchips as thermal insulation to assist slope stability. Many river crossings along the route required the unavoidable crossing of ice-rich permafrost slopes. While the pipeline itself was thermally almost neutral, it was known that just clearing the surface vegetation would result in unavoidable thaw, with the potential of damage to the pipeline. Spreading up to a metre thick or more cover of woodchips allowed this effect to be suppressed.

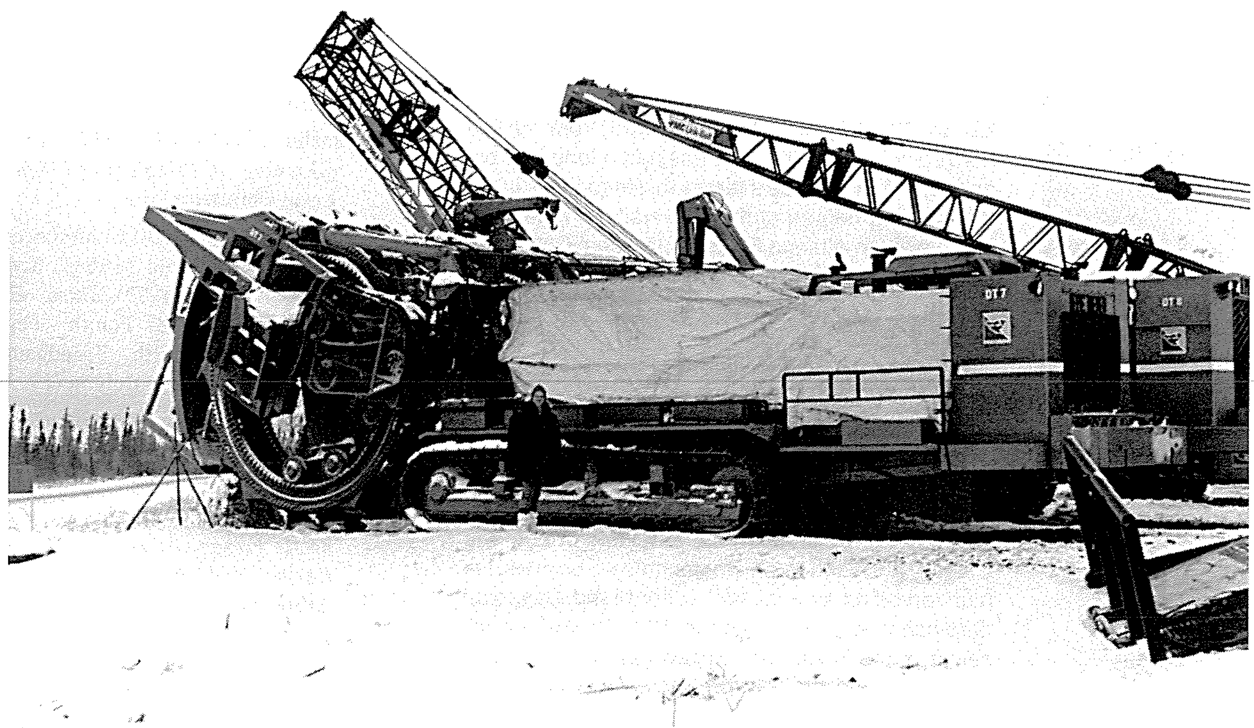


Russian side boom lifting pipeline on total project. [Photo Credit:Al Hanna]

In the last two decades many new mines have opened in the North, and have presented unique challenges. Geotechnical engineers have learned to work with, and not against, the challenges offered. For example, tailings dam designs in the far North, tend to rely on freezing of the core and downstream sections as a desirable second line of defence.

Recent studies have shown that problems, with buried water and sewer lines in the Baffin region, have been caused by excessive freezeback pressures in locally confined line segments, as the active layer freezes back. This has led to improved design and construction procedures, as more is learned about how to live with the permafrost environment.

As will be covered elsewhere in this



Arctic ditcher trials of equipment capable of excavating ditch in permafrost for large diameter buried transmission line. [Photo Credit:Al Hanna] journal, one of Canada's major frontier energy success stories are the Oil Sands mines of northern Alberta. These mines are located just south of the southern limit of discontinuous permafrost, but have long severe winters. Many of the problems of northern engineering are experienced in these mines, and knowledge gained in winter construction in the Arctic has been put to good use. Major tailings retention structures, built out of overburden fills, are being constructed or planned for winter-only construction, in order to both balance equipment requirements and to minimize introduction of water in moisture sensitive fills.

Finally, and with all the emphasis placed on mechanistic approaches, permafrost engineers, like their warm-weather geotechnical colleagues, have also maintained a healthy and of course necessary interest in both geology and the practical aspects of constructability. Information collected by geographical and geological- oriented researchers has expanded our knowledge of what is actually out there, and has clearly enhanced our capabilities. Our associations with the skilled professionals in the construction side of Canada's northern expertise, have allowed many reality checks with the practicalities of dealing with northern conditions.

It is ironic that, as the Cold War finally ended, and in fact after the Berlin Wall fell, Canadian permafrost engineers were busy developing the designs for and installing grouted piles for a new chain of cruise missile detection systems through the Canadian North.

It is satisfying that the next phase of activities for many Canadian permafrost engineers has seen the profession exporting geotechnical and related expertise to projects in Russia, many assignments being for major American and European oil companies and others for Russian companies. Canadian engineers have been working on oil and gas fields as well as mining developments in the European and Siberian Arctic, as well as export pipelines from Siberia through Mongolia and China to the Pacific coast.

Conclusions

The last half a century has seen a tremendous increase in the ability of Canadian geotechnical engineers in permafrost technology. We have made great progress in classifying, correlating and quantifying the peculiar nature of permafrost. We can provide credible answers to the range of questions listed earlier, and we have achieved a strong and mature branch of the Canadian Geotechnical Society.

We have come a long way, from that initial benchmark of only twenty English language citations and one Canadian, in Muller's 1943 permafrost book. Those of us who had the opportunity to participate in this development can be proud of our accomplishments.

ED MCROBERTS, who graduated from Whitehorse Senior High in 1961, has had a long interest and career in Canada's far north. He took his initial engineering degree at the University of Alberta in 1967, was an Athlone Fellow at Imperial College of Science and Technology, and completed a Ph.D. at the University of Alberta on the subject of permafrost slope stability.

After retiring from the Corps of Royal Canadian Engineers with the rank of captain, Dr. McRoberts joined R.M. Hardy and Associates in 1973 and is now the chief technical officer and senior vice-president of the successor firm AGRA Earth & Environmental.

Dr. McRoberts has been the president of both the Calgary and Edmonton Geotechnical Societies. He has served as an assistant editor of the *Canadian Geotechnical Journal,* and in 1995 he was co-receiver of the Roger J.E. Brown Permafrost Award for a paper on the Interprovincial Pipe Line from Norman Wells.

Acknowledgments

The author wishes to thank his permafrost colleagues W.A.(Bill) Slusarchuk and A.J.(Al) Hanna at AGRA Earth & Environmental for their helpful comments on this paper.

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Offshore Development in Canada: Marine Geotechnical Engineering

Jack I. Clark

The development of offshore engineering in Canada has been sporadic and in recent years has been driven by the oil and gas industry. Marine geotechnical engineering in Canada has developed over a period of about 100 years but growth has not been steady. Prior to about 1970, exploration experience in Canada was limited predominantly to the Great Lakes, particularly Lake Erie where over 50 wells had been drilled by 1955 (Appleton 1982). Most of the marine geotechnical work carried out was applied to the development of ports and harbours. An excellent presentation on the drilling techniques used for many of the early site investigations has been presented by Matich and German (1979).

Several geotechnical consultants had experience with overwater drilling and testing, up until the 1970s but there was no concentrated capability as was emerging elsewhere in the world. Before the construction of the first artificial island in the Beaufort Sea in 1973 there was very little research being conducted in universities or government laboratories related to the geotechnical engineering aspects of offshore development. As a result the geotechnical community was ill-prepared to respond to the sudden burst of activity in construction of artificial islands in the Beaufort Sea in the 1970s and early 1980s.

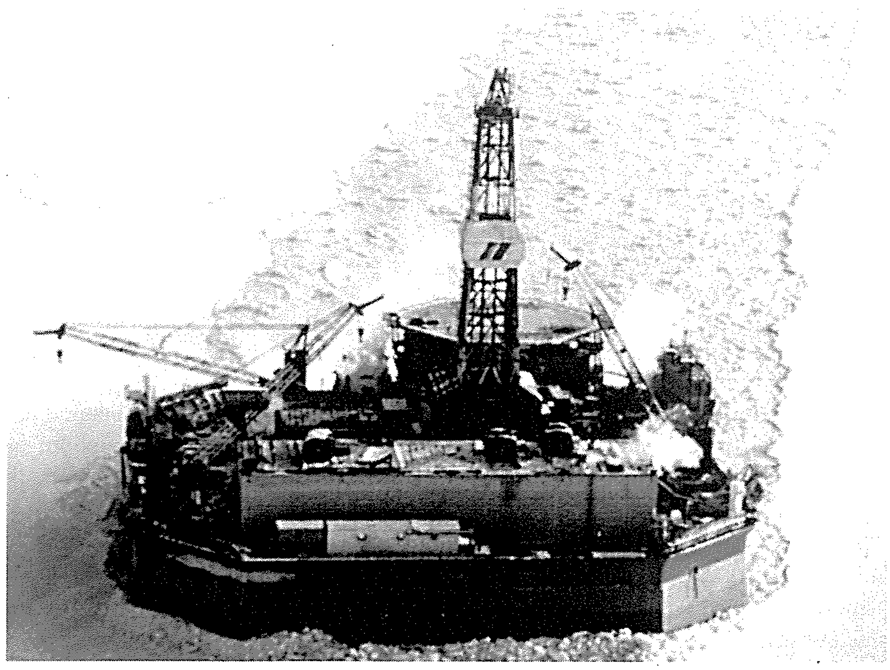

Photo 1. Tarsiut Island.

The initial offshore engineering work was dominated by firms from the United States and from the Netherlands.

As it became evident, however, that the permafrost regime was perhaps a more important consideration than the offshore drilling experience of the Gulf of Mexico, when applied to the relatively shallow water of the Beaufort Sea, Canadian firms with world-leading permafrost experience assumed an increasingly greater role in managing and conducting Arctic offshore investigations.

In 1976 the Associate Committee on Geotechnical Research of the National Research Council established a committee on marine geotechnical engineering. The first objective set for the Committee was to organize a conference that would bring together interested people from industry, government and the academic sectors. It was expected that the conference would provide case histories and a forum for discussion of research activities to identify Canadian strengths and weaknesses in offshore geotechnical engineering. The intent was to follow a similar and successful approach that was used to consolidate experience in permafrost engineering in 1972. At that time there was a very rapid growth in permafrost engineering both in field investigations and testing and in permafrost laboratories in relation to development of Arctic gas pipelines. International competition was intense. The National Research

Photo 2. The Molikpaq Structure.

Council established an Associate Committee on Pipelines which organized a conference in Kingston, Ontario in 1972. The conference brought together pipeline contractors, pipeline companies, oil and gas companies, government researchers, university researchers and consulting engineers. This event was a turning point for permafrost engineering in Canada as the geotechnical participants were able to demonstrate that capabilities for the geotechnical engineering required to develop Canadian northern pipelines resided in Canada and was well established. Canada quickly emerged as an important centre of leading-edge permafrost engineering and research as millions of dollars were dedicated to field work, laboratory testing and research.

The Marine Geotechnical Engineering Committee of the National Research Council organized the first conference to take place in Calgary in 1979. Six keynote presentations were delivered on subjects ranging from geoscience to construction with geotechnical engineering being the principal focus. In addition, thirty-one papers were presented and several discussion panels assembled to provide a compendium of case histories and research activities. In that regard the conference met its objective but in summing up the conference, Morgenstern expressed reservations on the Canadian capability because of what he referred to during the conference as "spasmodic pattern of development." On an optimistic note, he concluded that the ability to solve our problems did exist provided we could proceed in an orderly manner (Morgenstern 1979).

Offshore exploration activities in the Arctic went ahead at an accelerated pace and more and more of the Canadian consulting capabilities and research interests were directed to the unique problems of the Beaufort Sea. On the east coast of Canada extensive geoscience work had been carried out since the first well was drilled in 1966 but very little geotechnical engineering work was initiated until the plans for a gravity base structure to develop the Hibernia field were started in the mid-1980s. A second marine geotechnical conference was held in Halifax in June 1982. By that time the very active and vigorous program of exploration and construction in the Beaufort Sea had dropped off and both the consulting sector and the research community saw a rapid drying up of funds to support geotechnical exploration work and research. Attendance at the conference was as a result relatively low compared to the Calgary conference which caught Northern offshore development at the first surge of the wave. Nevertheless some 31 papers were presented but only about 20 of these found their way into print. The national energy policy prorogated by the federal government drove many of the oil and gas exploration production operations out of Canada to countries with more favourable development regimes, and the development in the Beaufort Sea and exploration on the east coast went into another hiatus. Activities in the Beaufort Sea emerged later in the 1980s but then underwent a complete shut down. The major oil industry companies had abandoned activities in the Canadian Beaufort by about 1990. The technologies developed for both drilling techniques and in-situ testing placed Canada among the world leaders in the Arctic offshore.

Meanwhile on the East Coast, activities were picking up as the Province of Newfoundland and Labrador moved towards agreement with the Federal Government on the development of offshore resources. The Atlantic Accord signed in 1985 paved the way for an increased level of geotechnical engineering and offshore design activities.

Geotechnical Challenges in Offshore Engineering

Beaufort Sea

The geotechnical conditions of the Beaufort Sea proved to be more complex than some had originally imagined. At one time it was thought that there would not be permafrost present below the water, but that proved not to be the case. Relict permafrost was encountered and in combination with the complex depositional processes introduced a formidable geotechnical challenge for construction of bottom-founded structures. Much of the geoscience work was carried out by government forces but the private sector consultants in Canada soon emerged as world leaders in site investigation, in situ testing and geotechnical design for Arctic offshore regions. The exploration pace was very rapid for a period of time, mostly driven by Gulf Canada, Esso Resources and Dome Petroleum.

Most of the artificial islands exploration were constructed by Esso starting in the early 1970s. The first islands were constructed by trucking gravel from the shoreline and dumping it through the ice to build a platform that was then used for exploration drilling during the open-water season. As the exploration interests moved further offshore into deeper water, dredged surface-piercing sand islands were constructed. Experience showed that very flat slopes were required to maintain stability, hence the economics for this type of structure were only favourable for relatively shallow depths. With exploration drilling pushing further seaward a new type of exploration structure was required. This led to the hybrid island, typically consisting of a low dredged berm on the bottom with a caisson-retained sandcore piercing the surface. Several types of structures were developed; the Tarsiut Island was made up of four large concrete caissons that were built in Vancouver, towed into place and then sunk to form an octagon structure. The core was then filled with sand. This was the only made in Canada structure. Other structures were made of steel, one called the CRI (Caisson Retained Island) built by Esso and the Molikpaq single hull built by Gulf. The most recent structure was a ship shaped model hull constructed by Dome Petroleum and still in use in other parts of the world today.

The construction of the artificial islands for exploration was carried out to standards that would be significantly less rigorous than would be used for a production platform, since they were only usually required for one drilling season at any one location. About 25% of them experienced either construction difficulties or post-construction geotechnical problems. Over 30 artificial islands were built but there were only a few case histories published. Examples of the kinds of problems that were experienced were Adgo Island which was a sand bag retained island that experienced instability of the classic circular arc failure (Shinde et al. 1986), Issungnak Island which was a surface-piercing dredged island where the upper portion disappeared twice during construction (Shinde et al., 1986) and the well-known Molikpaq Caisson Retained Island. The Molikpaq experienced partial liquefaction of the sand core in the spring of 1986.

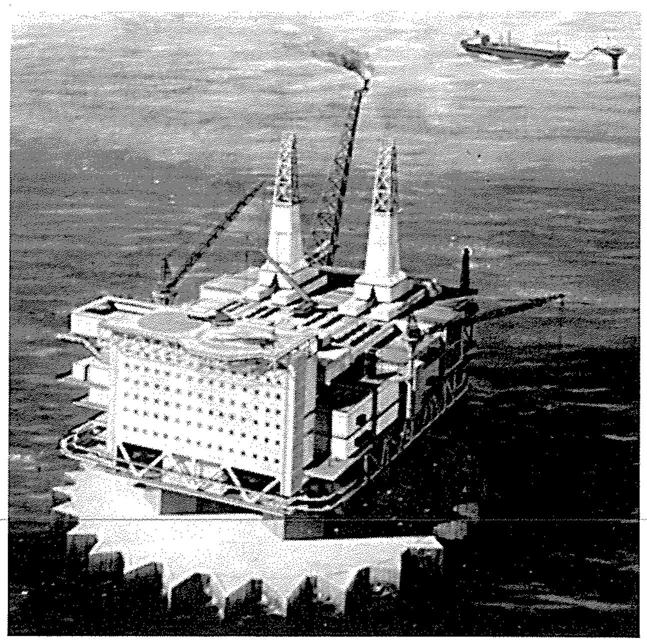

Photo 3. Artist's concept of the Hibernia GBS.

During this period of Arctic offshore engineering work major advances were made in sampling and in situ testing techniques. A great deal of the work found its way into the literature. The experience gained leaves the industry and Canadian consulting community well positioned to meet the challenges of design of production structures when a producable reservoir is identified. The fact that at present several reservoirs are marginal, presents the major challenge of developing more cost effective means of dealing with ice loads and associated construction challenges as well as innovative foundation systems for production platforms. At one time it was thought that the Amauligak Field was the "elephant" that would trigger the start of production from the Beaufort Sea. Subsequent step out drilling showed the reservoir to be less extensive than first thought. Following that revelation there was a gradual wind down of exploration drilling activities in the Beaufort Sea. At this time exploration is proceeding in the Alaskan Beaufort Sea with support from Canadian research and consulting and there are indication that exploratory drilling will be renewed in the Canadian Beaufort.

East Coast

The first production system for the East Coast of Canada, was the Cohasset-Panuke field platforms on the Scotia shelf. The Scotia shelf had been subjected to substantial oil and gas explora-

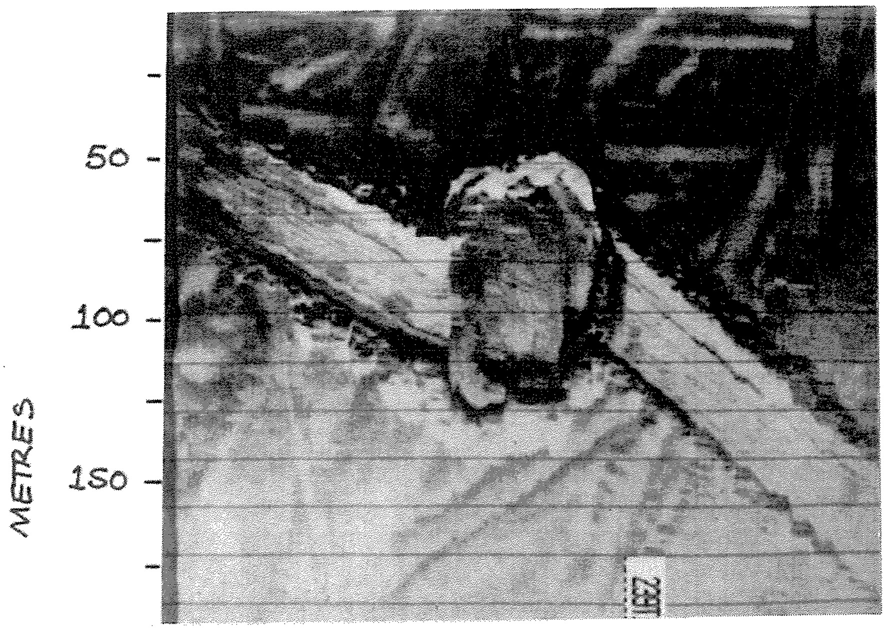

Photo 4. Ice Scours on the Labrador Banks.

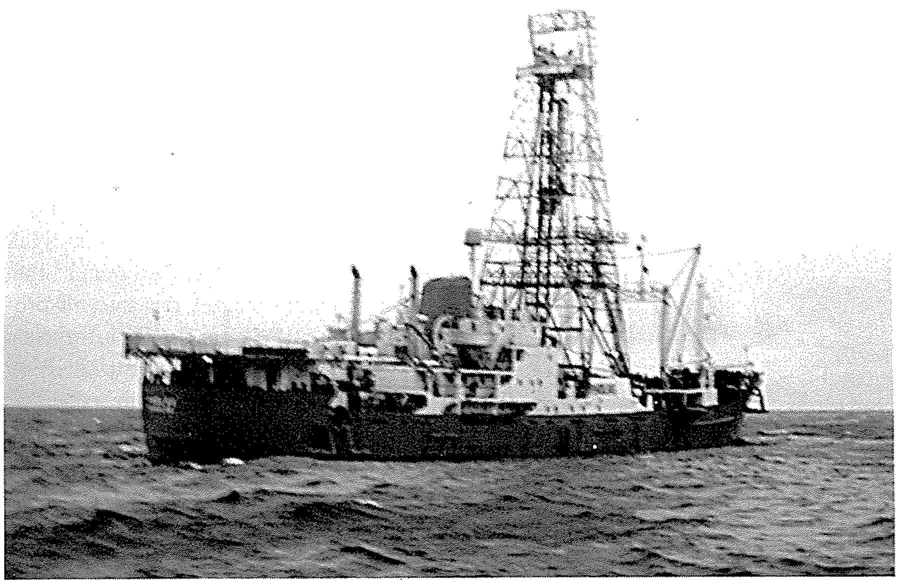

Photo 5. The Geotechnical Drill Ship "M.V. Pholas."

Summary of Canadian Marine Geotechnical Conferences

Conference	Location	Papers Presented	Canadian Papers
1 - 1979	Calgary	36	34
2 - 1982	Halifax	31 (21)*	9
3 - 1986	St. John's	48	39
4 - 1993	St. John's	66	46

** only 21 papers in preprints*

tion drilling programs and a number of geoscience investigations were carried out.

The Cohasset-Panuke field presented geotechnical challenges because it was the first offshore oil development in Canada and was in an area known to have a fairly mobile sand bed. A very good description of the geotechnical challenges has been presented by Taylor (1993). At the time of writing a pipeline to connect gas reserves from the Sable Island Bank to the mainland is being designed. The development will include new production platforms in the vicinity of Sable Island. Further east the Hibernia platform triggered a large amount of geotechnical exploration work. Canadian organizations participated in the site exploration but most of the geotechnical design of the Hibernia structure was carried out by the Norwegian Geotechnical Institute, drawing on their experience from the foundation design of many of the gravity base structures for the North Sea where over 75 have been built. The Hibernia structure will be the first gravity base structure on the Grand Banks and it will probably be the only one built unless there is another elephant discovered that has the reserves to make this type of structure economical.

At the present time, development plans are being produced for the next offshore field, that being the Terra Nova where it is expected that the platform will be a floater of some type. The system that is selected will be known by the time this is published. The geotechnical demands will be less than for the Hibernia structure but nevertheless the challenges will be of great interest to the geotechnical community. Protection of seabed facilities and wellheads against potential ice scour and reliable anchor systems are but two issues that will be dealt with. The extensive experience gained through the exploration phase of the Grand Banks that has been going on since 1969 as well as the design work for the Hibernia platform produced a knowledge base whereby the design challenges can be met by the Canadian capability. The foundation conditions for structures on the Grand Banks are generally very good, indeed much more favourable and less challenging than those of the Beaufort Sea. The major challenge for production facilities on the Grand Banks is understanding both sea ice and glacial ice (icebergs) as they affect the structure and seabed.

The Hibernia structure has been designed to resist iceberg impact but other structures will likely rely on ice management methods to combat this problem.

Present Status of Offshore Geotechnique

As described earlier, the 1979 Conference on Marine Geotechnical Engineering provided a database for the Canadian geotechnical community to assess its capability and consolidate case histories. It was recognized at the time that as a community we were responding rapidly to offshore engineering challenges but at that time we were not well prepared for the challenges that would be faced in the coming years.

By 1982, when the next conference was held, much of the work in the offshore that was initiated earlier had been dropped, but it accelerated rapidly for a short time thereafter.

By 1986 when the Third Geotechnical Conference was held in St. John's there was an exceptionally strong Canadian presence and a clear demonstration of the capability that had been developed within the consulting community, research institutes and government organizations.

The Canadian Marine Geotechnical Conferences have evolved over a period of 15 years. The growth in the number of papers presented and the number of Canadian presentations are shown in the table. The increased number of contributions from other countries also reflects the growth of interest in developments in the Canadian offshore. Many Canadian consulting companies are also now providing services to offshore development in other countries, particularly in Arctic regions.

An orderly development of offshore production facilities is expected for the east coast. The development of the Hibernia field will be followed by Terra Nova then likely Whiterose and Hebron Fields. Meanwhile, in the Canadian Arctic, the "elephant" will lie sleeping until probed by an exploration well which will then trigger another surge in Arctic activities.

Although the level of effort directed to offshore geotechnical engineering has been sporadic, there remains a very strong base of research and design capabilities which will serve the country well in the future years as development for production continues. The Canadian industry is well positioned to respond to the challenges.

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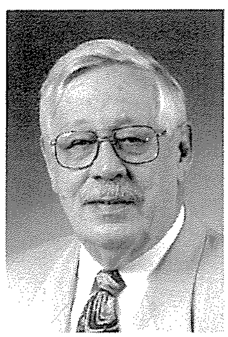


JOHN (JACK) I. CLARK received his initial degrees from Acadia University in math-physics, 1955, and in civil engineering from Nova Scotia Technical College, Halifax, 1957. Subsequently he took graduate studies at the University of Alberta and received his Ph.D. from Nova Scotia. In 1993 the Technical University of Nova Scotia conferred an honourary Doctor of Engineering degree on Clark.

Starting in 1957 Clark has had extensive engineering experience, as an RCAF construction engineering officer in the far north, and with the firms Northern Engineering Services, Hardy Associates, Golder Associates, HBT AGRA, and J.I. Clark and Associates. Recent projects include design reviews of the foundations of the Hibernia project and of the SCI Northumberland Strait Bridge.

Since 1984, Dr. Clark has been president and CEO of C-Core – Centre for Cold Ocean Resources Engineering, a research institute in St. John's with a staff of 60, which pursues research in advanced technology: remote sensing, seabed geotechnics, ice engineering, centrifuge modelling, intelligent systems, and space systems. Dr. Clark is also a Professor of Engineering at Memorial University of Newfoundland. He has authored over 80 publications.

Dr. Clark has participated in technical committee and professional organizations, and is the recipient of many honours and awards. A past president of the Canadian Geotechnical Society, he is a recipient of the Legget and Meyerhof awards and in 1996 delivered the R.M. Hardy Keynote Address. He has received the Julian C. Smith Medal of the Engineering Institute of Canada and the Xerox Canada Forum Award for furthering corporate – university cooperation in the field of research.

Oil Sand Geotechnique

Norbert R. Morgenstern and J. Don Scott

The Resource

The Alberta oil sands, contain about 270 billion m^3 (1700 billion bbl) of bitumen with somewhat less than 10% lying at depths sufficiently shallow to be surface-mineable. Estimates suggest that about 60% of the surface-mineable deposits are recoverable with current technology.

At this time there are two commercial operating mines. Suncor Inc. produces about 4.5 million m^3 (28 million bbls) of synthetic crude oil per year while Syncrude Canada Ltd. has an annual production of 11.6 million m^3 (73 million bbls), a total of 17% of Canada's petroleum needs.

In-situ recovery from deeper deposits has been a matter of experimentation with a variety of steam injection, combustion and solvent-based techniques. Commercial-scale recovery is restricted to the use of steam injection techniques.

The exploitation of this vast resource raises many geotechnical issues and has provided special opportunities for the Canadian geotechnical community. Geotechnical engineering not only makes essential contributions to the success of the mining operations and the resolution of their attendant waste disposal problems, but it also has contributions to make to the success of the in-situ recovery process.

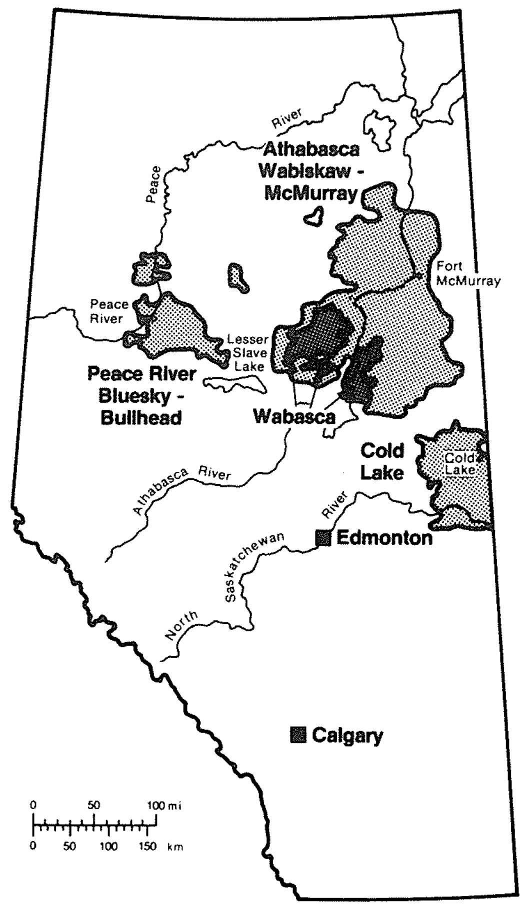


Fig. 1. Location of Alberta Oil Sands.

Geological Setting

Commercial mining is restricted to the Athabasca deposit in the vicinity of Fort McMurray; only the geology in this area will be summarized. The deeper Cold Lake and Peace River deposits differ from the Athabasca, particularly in terms of mineralogy.

The oil sands of the Athabasca deposit are generally composed of the Lower Cretaceous McMurray Formation, which comprises 35-75 m of uncemented quartz sand and associated shales. Where the sands are clean, porosity is high, as much as 35%, and bitumen saturation of 10 - 18% (by total weight) is common. The sands have suffered very little post depositional changes due to cementation or pressure solution etc. Hence the variations of permeability, bitumen content, and structures reflect directly the primary facies distribution.

The McMurray Formation rests unconformably on truncated Upper Devonian strata composed mainly of limestone and calcareous shales. Initial infilling of the McMurray trough appears to have taken place in a wide variety of fluvial-deltaic environments. Subsequently there developed a regime marked by the presence of very deep channels, which locally incised through the pre-existing sedimentary sequences and desposited a characteristic fining-upward sequence composed of cross-bedded channel-bottom sands at the base, then lateral accretion deposits laid down on the sloping flanks of channel-margin bars in very large channels, and finally argillaceous sands of flood plain origin. Clay drapes formed in the lateral accretion deposits prove to be of major geotechnical significance.

Fig. 2 illustrates the channel cut-and-fill structure that characterizes the McMurray Formation. In many instances it is not possible to establish stratigraphy over a distance greater than 50 m. Nevertheless slope stability for safe mining has to be assessed over accumulated distances of hundreds of kilometres. Understanding the complexity of the deposit by means of sedimentary facies has proved as valuable an indicator of potential geotechnical problems as it is of ore grade.

Mine Slope Stability

The development of large-scale mining equipment over the past three decades has facilitated economical surface mining of the oil sands. Suncor, which began mining operations in 1967, initially utilized bucket-wheel excavators, which fed onto moveable mine conveyors, whereas Syncrude adopted at the outset a combination of draglines, bucket-wheel reclaimers and moveable mine conveyors. The mining arrangement at Suncor adopted 20 m high working faces separated by wide benches and it experienced minimal problems in terms of pitwall stability.

At Syncrude, a single-bench dragline scheme with pit highwall depths extending up to 60 m is utilized for mining the oil sands (fig.3). The ore is windrowed parallel to the highwall crest and subsequently reclaimed by the bucket-wheel reclaimers and conveyed to the extraction plant. Overburden is prestripped by mobile equipment outside the active mining area and disposed of both in and out of the mined-out pit. The mine consists of four quadrants, each of which has an independent dragline—bucket-wheel reclaimer— conveyor system. The draglines are not "off-the-shelf" items. Replacement cost is high. Perhaps even more important is the potential loss of production to this continuous mining operation in the event of the loss of a dragline. The initial Syncrude design team and subsequent operations staff had to demonstrate that it would be safe to mine continuously with draglines set directly on the oil sands formation.

The study of natural slope stability in the oil sand deposits and the behavior of a large-scale trial excavation supported the view that dragline mining was both feasible and safe. Nevertheless the geotechnical behavior of the oil sands was enigmatic and a better understanding was needed to proceed with dragline mining in a confident manner.

Hardy and Hemstock (1963) published the first attempt to understand the strength characteristics of the Athabasca oil sands. They noted that compressive strength of nominally undisturbed samples decreased with depth and they recognized that this was due to gas evolution resulting in swelling and disruption of the sand fabric. This historically significant study recognized that the unique behavior of the oil sands was related to the interaction of its four phases: sand, bitumen, water and gas.

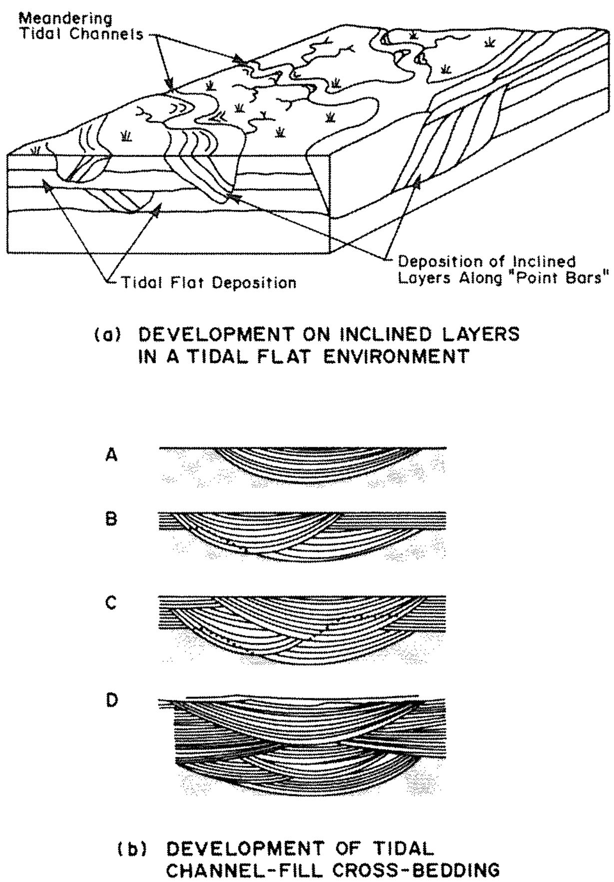


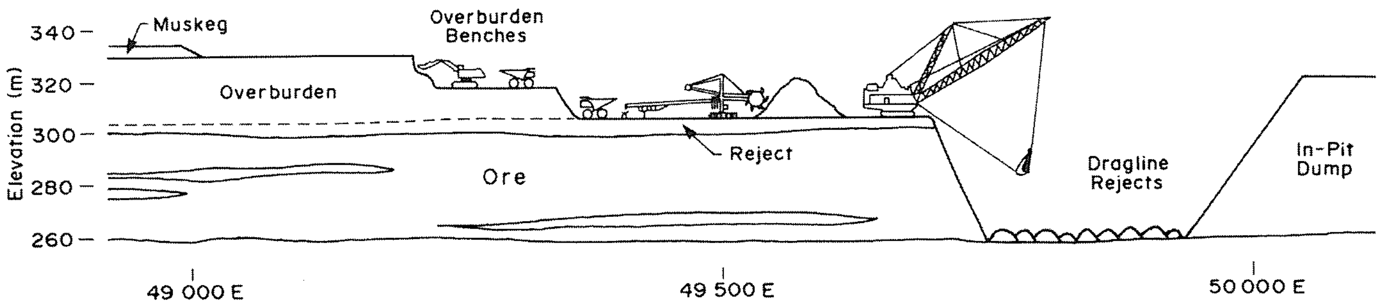
Fig. 2. Development of tidal channel fill structure.

The needs of the Syncrude project provided considerable impetus to develop improved sampling and testing procedures in order to better determine the shear strength properties. Ultimately it was shown that the frictional strength of oil sands at in-situ void ratios were in the order of 50-60, consistent with deductions from natural slope studies. The fabric of the oil sand was shown to be responsible for the high strengths and when this fabric is destroyed, it behaves as a normal sand. Under load for geological spans of time, an interpenetrative but uncemented structure that has been called "locked sand" develops which has high strength due to enhanced dilatant characteristics. In-situ, the pore fluid, particularly the bitumen, contains significant quantities of dissolved gases which, upon release of confining pressure, come out of solution. The relatively low permeability of the oil-rich sand does not permit rapid dissipation of evolved gas and the net outward pressure results in gross fabric disruption by expansion.

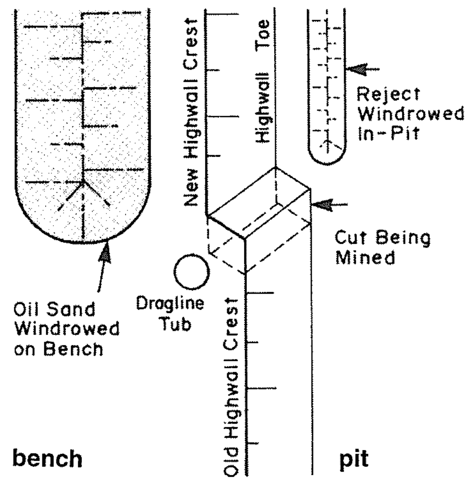
These findings gave Arthur Casagrande, who was one of Syncrude's advisors, considerable pleasure. He related to one of us that he and Terzaghi knew in the late 1930's that "when you leave sand under load for a long time something happens to it." They had thought that strength enhancement arose from long-term contact growth between sand grains, but laboratory tests to demonstrate this behavior had not been successful. The locked sand concept was found to be equally relevant to explaining the earlier interests of Casagrande and Terzaghi into the behavior of the St. Peter Sandstone. With confidence in the overall shear strength of the oil sands, attention could be focussed on the very significant hazards associated with the clay seams within the ore body.

These clay beds were formed in the various tidal channels, in which abandoned channels were filled with layers conforming to the shape of the scoured-out channels and in active migrating tidal channels, where the dipping clay beds were formed by lateral accretion of channel point bars. These clay beds can dip 20° or more, normal to the channel axis. Their lateral continuity depends on the width, depth and degree of meandering of the channel, all features difficult to characterize economically by routine site investigation techniques.

The presence of these dipping clay beds and associated shear strength properties, combined with locally high piezometric pressure due to gas evolution,



a) CROSS SECTION



b) PLAN VIEW

Fig. 3. Syncrude dragline mining scheme.

cause block slides to occur (fig.4). Syncrude's original Geotechnical Review Board was very concerned with this failure mode and emphasized the on-going need for an observational approach to mitigate risk associated with sudden block slides directly affecting the dragline.

The Board operated in the mid-1970s at a time when risk analysis in geotechnical practice was seldom applied in a formalized manner. Nevertheless, the Board reflected on these matters and advised Syncrude that notwithstanding the best conceivable practice of the time, Syncrude would have to reckon on the loss of one dragline every ten years as a risk cost associated with the dragline-mining scheme.

Commercial mining began in 1977, and one can imagine the pleasure a decade later for those involved in the mine when decals were produced celebrating ten years of safe dragline mining. It is now twenty years of safe dragline mining. Over forty block slides have developed. Unanticipated failure modes, due to slow flow of the highwall in gas-rich ore and associated crest retrogression, have also been encountered and managed effectively.

Oil sand projects operate with a culture of continuous technical improvement and both mining practice and geotechnical monitoring have participated in this process. Over the years the skill of highwall engineers and dragline operators has improved enormously. New geotechnical monitoring tools, such as remotely operated continuously monitoring slope inclinometers, have been developed and a monitoring system of considerable subtlety, honed by experience, has been put in place.

One of the major breakthroughs in this regard has been the utilization of the small-diameter dipmeter which provides reliable information on the attitude of critically oriented clay seams in advance of mining, and when used together with highwall mapping and ongoing assessment of past highwall performance, has provided a monitoring system that exceeded the vision of the original designers.

It is now twenty years of dragline mining at Syncrude and the end is in site. Suncor has already abandoned its bucket-wheel operation in favour of a high capacity truck-shovel operation and Syncrude will also be abandoning its draglines in favour of truck-shovel operations when it advances into new mining areas. The geotechnical community can take considerable pride in its contribution to this successful phase in the unfolding story of oil sands development.

Cold Weather Construction

Continuous mining operations require continuous excavation and transport of ore. They also require continuous utilization and disposal of waste materials. The climate of the Athabasca region is sub-Arctic continental with cold winters and warm summers. The mean annual temperature in Fort McMurray is 0C. Winter temperatures reach -45C and weeks of -30 to -40C are not uncommon. During November - April, temperatures seldom rise above freezing. Plant productivity is maintained throughout the winter months, although periods of extended cold take their toll on men and machines, affecting mine output.

The negative effects of winter climate are mostly associated with dyke and tailings dam construction activities. Because of fog generation problems, tailings dykes are not normally built during winter months and the entire stream is beached. Traditionally construction of other large retention dykes, composed of overburden and dry mine waste, was also restricted to summer months. However pioneering work at Suncor indicated that it was technically feasible to build in-pit overburden dykes year round. Cold weather earthworks was advanced to a remarkable degree by the construction of Syncrude's Highway Berm.

In the early 1990's it became apparent that by constructing a berm across the mine that would act as a dam to store fluid tailings, as well as provide a platform for relocating most of the plant utilities, including a major highway, sufficient additional reserves would be accessed on the side of the mine that a new mine opening could be delayed by about two years. The deferred capital cost and additional time provided by this relocation was very attractive financially and operationally. However, with engineering still on-going, construction had to start in February, 1992; three of the powerlines were required at the 50 m fill height by September, 1993 and the highway was required to be open at the 63 m fill height by September, 1994. To accomplish this, Syncrude had to construct a berm 2.5 km long, 63 m high with a volume of 42 x 10^6 m^3 over a foundation of mine pit bottom and dragline reject materials. The berm had to function as a dam for a number of years. In addition, it had to be constructed of mine waste materials with mine equipment, and obviously required placement throughout two full winter seasons to meet production targets in an economical manner. Many challenges had to be overcome but the success in establishing winter construction methods, utilizing the mine's heavy haulers to achieve compaction of relatively thick lifts, was particularly striking.

Winter construction required excavating non-frozen fill from borrow sites, placing and compacting the fill before it freezes and cleaning snow and ice from the construction area prior to placement of subsequent lifts. Excavation was relatively straightforward, given the size of equipment available at the mine site and the need to remove all overburden for oil sands mining. However placement and compaction prior to freezing and lift clean-up operations were very challenging.

Off-road haul trucks of 170-195-or 240-ton payloads were used for both placement and compaction. Unfrozen fill was delivered and compacted in a timely manner to prevent fill from freezing while at a density less than that required. The time available for compaction was a function of fill moisture content and ambient air temperatures. At about -35C, the fill had to be compacted within about 30 minutes of placement. This required close co-ordination between engineers and operators, but ultimately proved practical. Winter compaction to the necessary specification was attained at temperatures as low as -47C.

The berm was available on time and has performed well within design parameters. It constitutes a major advance in winter earthworks construction, particularly relevant to large-scale resource development projects.

Fig. 4. Shear surface on dipping clay bed; dragline in background.

Tailings Dams

While oil sands mining and extraction projects move materials on a grand scale, they also generate waste on a grand scale. Both operating plants produce wet tailings. The management strategy in each case requires out-of-pit storage by means of a tailings pond, until sufficient space has been created to turn to in-pit storage.

The tailings are predominantly a mixture of uniform fine-grained sand and water, but also contain well-dispersed silt and clay as well as some residual bitumen. On deposition in a tailings pond, the sand fraction settles out to form dykes and beaches and the oily silt and clay fraction suspended in the water forms a sludge, called fine tailings, that flows into the pond. All of these materials must be stored since only a portion of the water in the pond is clean enough for re-use in the plant. Practice indicates that, in the early years of mine development, the storage volume required is about three times the volume of oil sand mined and processed. As pond sedimentation processes mature and water recycle becomes possible, a bulking factor of 1.4 is appropriate.

The characteristics of segregating tailings noted above and the resulting large storage requirements were not understood by the initial designers of the Suncor operation. The initial design of the out-of-pit storage contemplated a perimeter dyke about 12 m high. This was constructed of overburden and built directly on muskeg and alluvial deposits in the Athabasca River Valley. Tailings discharge was planned to be from the top of the adjacent valley wall which was some 60 m above river level. The tailings sand was assumed to form a stable 8% slope. This facility would only have a 3-year life.

Construction of the retention dyke began in 1966. At this time, as a result of pilot studies, it also became clear that the 8% slope would not be realized and that the bulking factor had been underestimated. This dyke, Tar Island Dyke, was modified to provide a final height of 23 m, based on an overburden cross-section.

Suncor went into operation in 1967 and, due to operational difficulties required even more storage. Moreover overburden construction was proving excessively costly and could not be produced within the mining plan. Dr. R.M. Hardy and the general contractor, Mannix Co. Ltd., came up with a series of innovations that transformed the design from conventional overburden placement to hydraulic placement followed by compaction. Tar Island Dyke was ultimately completed to a maximum height of 98 m. It is about 3.5 km long and is founded partly on normally consolidated clay. Construction of Tar Island Dyke has been a field school for many tailings retention structures that have followed, both in the oil sands industry and elsewhere in the world. It has provided unique experience in hydraulic fill construction, static liquefaction, settlement and creep of soft clays, progressive failure processes, and site closure planning, to cite some of the more challenging issues.

The main tailings dyke at Syncrude followed construction procedures developed at Suncor, but had different challenges due to its size and difficult foundation conditions. The Syncrude tailings pond is designed to provide storage for 550 10^6 m^3 of sand, 370 x 10^6 m^3 of fine tails and 50 x 10^6 m^3 of free water. To accommodate these volumes, approximately 18 km of dyke ranging from 32 to 90 m in final height and enclosing a 22 km^2 surface area, has been constructed. In terms of volume of engineered fill, this is one of the largest earth structures in the world.

The tailings dam has been constructed on till overlying high plasticity Cretaceous clay shales (Clearwater Formation), which are followed by the dense oil sand formation. Glacial drag processes have sheared the clay shale in-situ to its residual strength which is very low. In addition, the low permeability of the fine-grained clay shales results in exceptionally low rates of dissipation of excess pore pressure consequent upon construction. Thus a combination of low shear strength and high pore pressure leads to low Factors of Safety.

The original design anticipated overall downstream slopes of 3:1-4:1. Foundation movements in the Clearwater Shale, during construction of starter dykes, alerted the designers to potential foundation stability problems. Construction proceeded with comprehensive monitoring, based on the observational method, to isolate those sections requiring remedial treatment. In sensitive locations it was necessary to flatten the slope to 9:1 in order to achieve ultimate height.

Working with such a weak foundation highlighted the limitation of design based on factor of safety considerations alone. Ultimately more reliance was placed on monitoring the strains in the foundation and interpreting allowable movements, with the assistance of advanced finite element analysis. Slip displacements in excess of 30 cm were safety accommodated during construction. Constructing critical hydraulic fill structures under these circumstances also required that attention be paid to the potential for triggering static liquefaction.

The successful completion of the Syncrude tailings dam is a testimony to the value of the observational method in practice. Major advances were made in hydraulic fill compacted cell construction, the understanding of clay shale behaviour, liquefaction characterization, foundation monitoring, and analysis of dam foundation movements controlled by a weak layer.

Fine Tails Management

The sludge or fine tails which has accumulated in the tailings ponds is considered toxic and presently 400,000,000 cubic metres are being stored. This volume is increasing annually by over 30,000,000 cubic metres. The most promising strategies for long term containment involve: 1) incorporation into a wetland with biodegradation of toxic leachate, 2) incorporation by mixing into coarser tails or overburden in order to reduce volumes, and 3) adding admixtures to transform the tailings stream from a segregating into a non-segregating material, thereby maximizing fines capture. Additional investigations are exploring dewatering by freeze-thaw processes and by atmospheric drying.

Fig. 5. Scanning electron microscopy showing clay card-house structure of mature fine tails at a void ratio of 5.

The mean particle size of the fine tails is between 5 and 10 microns. The average solids content of mature fine tails is about 33% which is an average void ratio of 5. The permeability of mature fine tails is in the range of 1 x 10^{-6} to 1 x 10^{-9} m/s which accounts for its slow rate of consolidation. In addition, the fine tails exhibit a thixotropic character that influences its long-term densification. Although the predominant clay in the fine tails is kaolinite, bicarbonates and napthanic acids in the extraction water result in the clays forming a cardhouse structure, which is stable at large void ratios (fig. 5).

Both mine operators propose to utilize constructed wetlands as a natural bioreactor before process water enters the river system. In the wet landscape option proposed by Syncrude, fine tails will be pumped into mined-out areas and reclaimed by covering with a layer of water to form a lake. The water-capped lake is intended to become a stable self-sustaining ecosystem with acceptable levels of diversity and productivity. The geotechnical concern here is evaluating the long-term consolidation of the underlying fine tails, where the release water would be continually contaminating the lake water.

The most effective new disposal option to date involves changing the tailings stream into a nonsegregating material, to eliminate the production of additional fine tails material, adding fine tails from the present inventory volume and co-disposing the mixture to form a sand deposit. Comprehensive laboratory studies at the University of Alberta and field demonstrations by both Suncor and Syncrude have shown the validity of this process and it is being adopted at a commercial scale. The process is being called composite or consolidated tailings.

Scanning electron microscope analysis of the fines in the oil sands tailings has shown a unique cardhouse structure that is stable at void ratios as high as 9. The addition of calcium containing chemicals does not change the cardhouse structure, but increases its strength so sand grains can be supported in a fines matrix with void ratios as high as 6. If enough sand is added to the fines matrix, the sand acts as an internal surcharge and the sand mass consolidates the fines to fine void ratios of 3 to 4. With 75% to 80% sand by mass in the nonsegregating tailings, the sand grains begin to touch one another at a total void ratio of about 1 under a consolidation stress of only 5 kPa. Compressibility at higher stresses is then mainly governed by the sand structure, not the fines structure. Permeability, and therefore the rate of consolidation, is always governed by the fines structure. The nonsegregating tailings is therefore an unique composite geotechnical material. It is of interest to note that geotechnical engineering has been able to contribute to the processing of tailings in addition to their containment.

In-Situ Recovery

Development of the oil sands using in-situ techniques began in earnest some

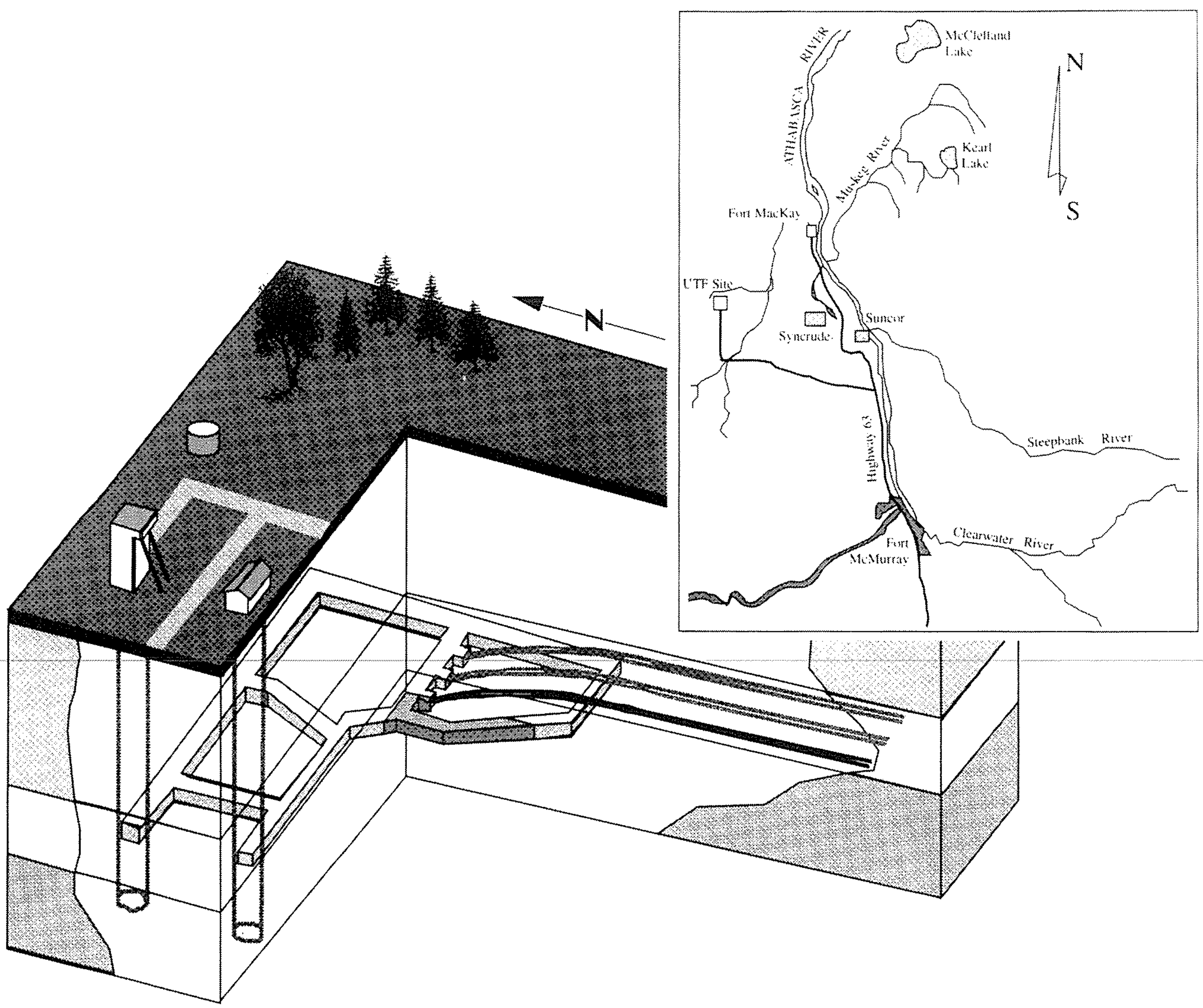


Fig. 6. Location and layout of underground test facility.

25 years ago and has steadily progressed from isolated experimental testing to major commercial development. Presently eight commercial projects in the Cold Lake and PeaceRiver deposits are producing 8.4million m^3 (52.8 million bbls) of bitumen per annum. With 90% of the Athabasca deposit and all of the Cold Lake and Peace River deposits being too deep for surface mining, insitu oil sand developments will become the major source of oil in Canada.

The role of geotechnical engineering in the in- situ extraction of bitumen from oil sands involves studying the stresses and deformations that occur in a formation due to changes in stress, pore fluid pressure and temperature. The geotechnical response of an oil sands reservoir to fluid pressure changes or to temperature changes results in stresses and deformations which affect hydraulic fracture propagation, formation shearing, fluid transport properties such as absolute permeability, production containment, well casing performance, the stability of underground openings (wells, tunnels and shafts) and the magnitude of surface heave.

Because the occurrence and the geology of the oil sand deposits are relatively well known, oil companies planning in-situ oil sand projects are not geological risk-takers as in conventional oil exploration; they are technology risk-takers. In-situ recovery has made major advances in the last several years. The first commercial venture, Imperial Oil's Cold Lake project, uses cyclic steam stimulation during which the formation is hydraulically fractured and steam is injected to heat the bitumen, which is then produced by the same well. The reservoir, the Clearwater Formation, is at a depth of 470 m and steam is injected at a temperature of 310C.

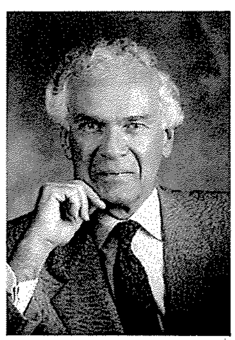
As hydraulic fracturing plays a dominant role in this type of production, ImperialOil has performed major geotechnical programs to determine insitu stress fields using minifrac tests. Observations and monitoring programs are employed to determine the direction and extent of the production fractures and their changes due to the thermal recovery process. The influence of the geotechnical behavior of the formation on bitumen production, and on well casing impairment is evaluated by the installation and monitoring of vertical control benchmark arrays, to quantify near-surface vertical displacements, and the installation of dedicated observation wells to monitor vertical and horizontal formation movements and reservoir temperatures and pore pressures.

The rapid advances in drilling horizontal wells and the development of a special form of steam flooding, known as steam assisted gravity drainage (SAGD) has, resulted in an in-situ process which recovers more oil than other steam stimulation processes. In conjunction with the Phase A trial of the SAGD process at the Underground Test Facility north of Fort McMurray (fig. 6), extensive geotechnical instrumentation programs were conducted in, below and above the reservoir, to evaluate the impact of geotechnical factors on the SAGD process and in the tunnels containing the high temperature (220C) wellheads, to monitor the performance of the tunnels for stability and safety concerns. As part of the geotechnical program, an extensive laboratory testing program was undertaken at the University of Alberta to examine the thermomechanical properties of oil sands and its intraformational shales and the underlying limestone.

Reservoir performance assessment during SAGD, the major objective of instrumentation installed for the Phase A steaming trials, was achieved with a wide array of instruments and installation techniques. Dedicated thermocouple, inclinometer, extensometer and piezometer wells were installed

Formation displacements within the reservoir capable of significantly influencing reservoir properties, specifically absolute permeability, have occurred during the Phase A SAGD test. Vertical extensional strains of 2.5%, horizontal extensional strains of 0.3%, volumetric strains of 2.5% and a 30% increase in absolute permeability developed as a result of the steam-assisted gravity drainage process.

The main objective of the tunnel instrumentation program was to ensure the integrity of the underground openings and wells. The tunnel instrumentation program involved monitoring the



NORBERT (NORDIE) R. MORGENSTERN graduated in civil engineering from the University of Toronto in 1956. On an Athlone Fellowship he researched and lectured at the Imperial College of Science and Technology, under the guidance of Professors A.W. Skempton and Alan Bishop, and was awarded his Ph.D.

Morgenstern returned to Canada in 1968 to the University of Alberta where he is University Professor of Civil Engineering and chair of the Department of Civil and Environmental Engineering. He is a recognized authority on landslides in shales, permafrost engineering, and geotechnical problems associated with the development of the Alberta Oil Sands.

Dr. Morgenstern has authored many technical papers and has received several honours and awards. His is a past president of the Canadian Geotechnical Society and the International Society for Soil Mechanics and Foundation Engineering, 1989-1993.

stability and the integrity of the rock in the vicinity of the heated underground wellheads, monitoring the stability and the integrity of the tunnels, and monitoring the stability of the underground injection and production well completions.

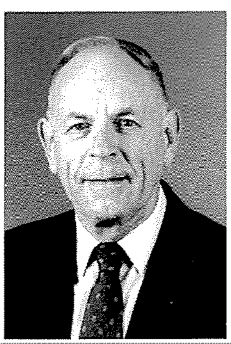
At the present time, a Phase B SAGD pilot is under way at the UTF with both reservoir and tunnel geotechnical monitoring instrumentation in place. The role of geotechnical considerations in in-situ recovery is gaining greater recognition.

The Future

The oil sand industry has completed a phase of reducing costs and expanding output while emphasizing the need for maintaining safety and environmental integrity. As a result of a recently clarified fiscal regime and the convergence of several new technologies such as modern truck-shovel mining to replace draglines, hydrotransport of ore to replace conveyors, nonsegregating tailings to enhance environmental integrity and cold water extraction methods to achieve energy savings, the industry is poised for substantial growth. Both Syncrude and Suncor have announced new mine developments and several billion dollars have already been committed to capital investment in the next few years. Expansion of in-situ extraction is also under way. One influential study documents an action plan to increase production capacity to about 365 million barrels per year, requiring a capital investment of $21 billion dollars over 25 years.

The technologies change and the role of the geotechnical engineer in the industry also changes. Geotechnically sensitive drag-line mining is being replaced by less sensitive truck-shovel operations. This raises new questions, such as how does one design optimum roads for the new 350-ton trucks being developed? Improvements in waste utilization and management are on-going. It is now time to restore the large areas of disturbed terrain and an integrated approach to this is evolving, termed Landscape Engineering, which relies considerably on geotechnical guidance.

There is little doubt that the expansion of the oil sand industry will continue to challenge the Canadian geotechnical community for many years to come.



J. DON SCOTT graduated in civil engineering from Queen's University, Kingston in 1954 and obtained his Ph.D. at the University of Illinois.

In a career spanning 35 years, Scott has been associated with five universities in Canada and the United States, in research and in administration to the level of department chairman. He has also been a principal of geotechnical engineering firms in Ontario, Quebec, and Alberta.

Joining the University of Alberta in 1980, Dr. Scott is now Professor Emeritus of Geotechnical Engineering. His major research and consulting activities have been in the field of geomechanics applied to the energy development and natural resource industries. He has held a research chair in the Alberta Oil Sands Technology and Research Authority and is head of the Geosynthetics Research Centre and of the Reservoir Geomechanics Group.

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Rock Mechanics Engineering in Canadian Surface Mining

C.O. (Chuck) Brawner

Introduction

Geotechnical engineering in surface mining in Canada was largely based on past experience until the early 1960s. Rules of practice were modified when instability developed. As open pit mines became more common and deeper, a number of geotechnical, geological and mining engineers realized that mine safety and economics could be improved by the application of geotechnical principles. By this time soil mechanics had become well developed but rock mechanics was still in its infancy.

In the east, Dr. Don Coates of the Canadian Department of Mines and Dr. Allan Bauer of Queens University and in the west, the author and Dr. Doug Piteau developed major interests in open pit mine stability and rock mechanics. Dr. Coates worked extensively in the iron mines near Schefferville, Labrador where the weak iron formation, permafrost and high water pressures impacted slope stability. Dr. Bauer developed the early guidelines for blasting and rock fragmentation. Dr. Piteau recognized the importance of structural geology in determining the type of failure that would occur. The author became primarily involved in evaluating and stabilizing movements that developed and in the design of open pit slopes. The major concern that arose was the desire to develop safe slopes as steeply as possible.

As the mines became deeper, more and more waste rock was produced. This blasted rock is deposited in waste piles. In mountain areas these have reached heights of 1,200 feet.

(Note - Examples described are historic. Hence, English units are used.)

This review will highlight some of the key geotechnical issues related to rock slope and waste dump stability with emphasis on case examples in Canada.

Early Developments

The author became involved in open pit problems in the mid 1960s at Schefferville, Labrador (Iron Ore Company), Gagnon, Quebec (Quebec Cartier Mining Co.), Highland Valley, B.C. (Bethlehem Copper) and Alice Arm, B.C. (Kennecott - B.C. Molybdenum). During this involvement, literature reviews indicated limited technical information and few locations where rock mechanics specialization had developed. The author arranged to spend time at Imperial College, London (Dr. E. Hoek), University of Karlshrue, (Dr. K. John),

Fig. 1. Canadian Johns Manville pit at Asbestos, Quebec. The slope adjacent to the town failed due to the sudden infiltration of water from a broken high-pressure water main. Over 30 million cu. yds. of material was involved. The slope was stabilized by a combination of unloading, horizontal drain installation and drainage into an underground adit.

University of Stuttgart, Germany (Dr. L. Muller), Civil Engineering University, Portugal (Dr. M. Rocha) and U.S. Bureau of Mines in Pittsburg and Denver.

It became apparent that mining engineers could improve safety and economics in surface mining by recognizing basic geotechnical concepts. Unfortunately, technical errors and misinformation was fairly common in the industry. Typical misconceptions included:

- Water is a lubricant.
- Water has little impact on stability.
- Large blasts improve mine economics without impacting stability.
- The flattest pit slope required is 37°, the typical angle of repose of broken rock.
- Pit failures will usually follow circular surfaces.

In 1966 an article was published in which these misconceptions were discussed, (Brawner, 1966). This was followed by the text, *Rock Slope Engineering* by E. Hoek, 1973 and the CANMET -*Surface Mine Geotechnical Manuals*, 1976 and three Mine Stability Conferences (1971, 1972, 1982) chaired by the author. By the early 1970s considerable new rock mechanics technology had developed.

More Recent Concepts

Important factors that became recognized are:

- Rock slope failure is largely controlled by the geological structure-joints, bedding, faults, *etc.* Failure modes include planar, wedge, block, toppling and buckling. Circular failure is only prevalent in weak and weathered rock. Development of the structural geological model has become a prime requirement for design.
- Rock strength determination requires an assessment of surface roughness. The direct shear test along discontinuities is most suited to determine peak and residual strength.
- The principle of effective stress applies to rock as well as soils. Pit slope and under-pit drainage is now standard practice. Drainage methods include horizontal drains, wells and adits. Vacuum assisted horizontal drains are recommended for large slides. Slope drainage usually allows steeper slopes, unless structural geology controls stability.
- Controlled blasting at and near the final wall reduces rock slope damage and also usually allows steeper slopes.
- Large-scale rock failure usually gives many months of advance warning such that a stabilization strategy can be developed. Monitoring of pit slope movement is now standard. Original procedures used hubs or extensometers across tension cracks. These have been replaced by remote reading Electronic Distance Measurement (E.D.M.) and most recently by satellite Global Position Survey systems (GPS). The most accurate GPS system available provides accuracy of ± 5 mm. Monitoring can also be used to forecast the time of slope failure to allow personnel and equipment to exit the mines prior to failure.
- High rock slopes which encounter weak rock near the toe create a special stability problem. The weak material becomes over-stressed and removes support for the upper slope. Failure develops over a shorter time period, fails at a much faster rate and with a greater than usual runnout distance.
- Stability analyses are now available for all of the major failure modes.

Canadian geotechnical engineers have developed an international reputation in open pit mine stability. Projects have been developed in all countries where surface mining exists.

Fig. 2. The failure extended into the town. The damage to this store was extensive. Fortunately there were no casualties.

To illustrate the variety and magnitude of mining geotechnical stability problems, six Canadian case examples are described.

Canadian Johns Manville, Asbestos, Quebec

In the late 1960s open pit mining had expanded and the pit began to encroach on the town of Asbestos. The pit had reached about 900 feet in depth. The ore body, containing serpentine ore, dipped at about 55° under the town. About 150 - 200 feet of overburden containing layered clays, sands, and gravels overlay the bedrock.

Lateral stress relief due to mining excavation lead to slope relaxation, minor cracking and opening of joints. A major water main in the town broke, releasing several million gallons of water into the overburden. Within 24 hours a major slide developed involving an estimated 30 million cu. yds. of soil and rock (fig. 1). The back scarp extended into the town and damaged many buildings (fig. 2). Fortunately no one was killed or injured. The scarp came within 75 feet of the primary crusher.

The author was contacted by the company president and arrived at the mine within 24 hours. The initial movement was about 15 feet. Movement continued at a rate of about 1 inch per day.

Most of the lower blast holes encountered water. This indicated that high water pressures likely existed in the slopes and had contributed to the failure. Following a review of the mine geology, mine dewatering and rate of movement it was decided to implement a two-stage stabilization program. This comprised unloading 2 million cu. yds. of overburden on the top of the slide area and a program to dewater the slopes.

A review of the mine plans revealed an abandoned mine shaft which lead to an underground development adit under the slope, about 100 feet below pit bottom elevation. The adit location was very fortuitous. The mine was requested to dewater and ventilate the shaft and adit. Drain holes were drilled upward from the adit to intersect the slide and develop vertical drainage. At the same time, about 20 horizontal drain holes were installed in the lower pit slope.

Within 2 months the movement was halted. This example illustrates the importance of pit slope dewatering. In most instances this will be the most economical stabilization program since most open pits today extend below the water table.

Lornex, Highland Valley, B.C.

A major toppling failure, involving about 25 million cu. yds., developed in the west wall of the Lornex open pit mine. The pit slope was about 800 feet high.

A series of clay infilled shear zones dipped into the slope at 55 - 70°. The shears were generally parallel to the main Lornex fault. The toppling cracks (fig. 3) developed across the west haul road and eventually lead to its relocation. Monitoring indicated movement increased with increased precipitation.

Slope indicator casings were installed over 450 feet deep. Movement of the casing occurred to depths of 300 feet. Horizontal drains were installed at several levels in the slope. The movements slowed but did not cease.

Later drains at the lowest levels were grouted for the outer 30 feet and a vacuum was applied. The rate of drainage approximately doubled. Movement continued intermittently. It was concluded that initial drainage did not commence soon enough—until after movement developed. Most mining has now shifted to the Highland Valley pit.

In the long term, removing another slice along the west wall is proposed. At that time it will be necessary to commence the installation of horizontal drains near the crest to reduce the potential of the initiation of toppling by water pressure buildup in the shear zones.

Fig. 3. The multiple cracks in the west side haul road at the Lornex Mine indicate a major toppling failure. The cracks have occurred along parallel clay-filled shear zones dipping at 55° - 70° into the slope. For a future setback, horizontal drainage should be installed near the crest and continued about every 100 feet in depth.

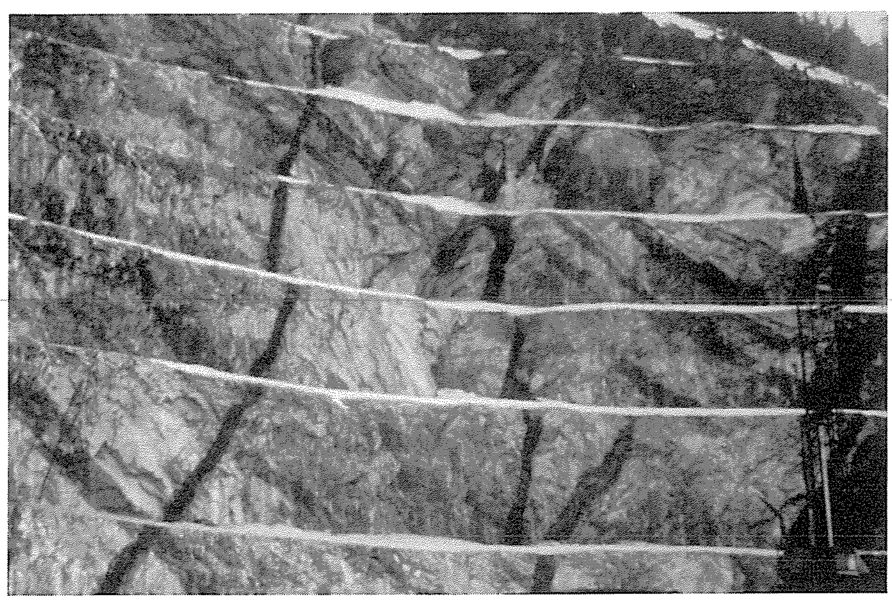

Fig. 4. One of the first examples of controlled blasting at a Canadian mine. The slopes at Westfrob Mine, Queen Charlotte Islands was developed at 55° with only local instability. Controlled blasting will often allow slope steepening by 5° - 7°.

Westfrob Mine, Queen Charlotte Islands, B.C.

The Westfrob Mine on the Queen Charlotte Islands mined iron ore in the 1950s and 1960s. It was one of the first mines in Canada to use controlled blasting.

It was recognized that the final pit slope of the mine would be damaged less and be more stable if the blasting forces were reduced near the final slope. The blasting involved drilling small-diameter closely spaced blast holes along the line of the final wall. One or two buffer line holes were drilled out from the wall at half the production hole spacing. Beyond the buffer holes, standard production blast holes were drilled. The final line holes were detonated first (presplit) about 20 at a time. The powder factor in the buffer and production holes was the same.

The wall rock was a competent limestone with the major dyke structure striking into the face. The controlled blasting procedure was so successful, two benches (double benching) were used for the first time in Canada. The resulting overall slope (800 feet high) was 55° (fig. 4), an exceptionally steep slope for that time.

During the last year of mine operations a high-grade zone was located in the toe area of the slope. The lower 120 feet was steepened to 70° using controlled blasting. The slope remained stable.

With our present knowledge, this slope could likely have been steepened to about 65°.

Line Creek Coal Mine, B.C.

The majority of coal mines in B.C. are located in mountainous terrain. The coal horizons range from near horizontal to steeply dipping. They are multi-layered and exist between layers of shale and sandstone.

At the Line Creek Coal Mine the lowest coal seam was being mined down a foot wall dipping at 35 - 45° into the pit. Over 400 feet of wall had been exposed. The rock below the coal was a thinly-bedded shale. Without warning a multi-layered slab buckled and failed rapidly onto the operating bench (fig. 5). Fortunately, no mining staff were working in the area.

Several factors could have contributed to the failure.

- Buckling stresses in the thin shale layers.
- Water pressure within the slope.
- Curvature in the bedding where stresses were greater.
- Cross-bedding which created a weak zone.

The first requirement was to stabilize the slope. The remaining portions of the slabs that had not failed had to be removed. A program of line drilling along the bedding and controlled blasting was developed from the top down. Following removal of this rock, a program to tie the beds together was developed.

Initially worn-out shovel cable was sandblasted to remove the grease, and grouted into 16-foot-long drill holes on

Fig. 5. A major buckling failure which occurred at the Line Creek Mine, B.C. in thinly layered bedded shale underlying the lowest coal seam. After removing the unstable slab, pattern bolting and pattern horizontal drains were installed to develop stability.

Fig. 6. A block slide that occurred at the crest of the highwall at Syncrude. Monitoring staff alerted the dragline operator who immediately began to move the machine away from the movement. Note the clay layer which dips toward the highway.

a square pattern. The concept was to increase the slab thickness—to reduce the buckling potential. Later, standard rock bolts were installed, tensioned and grouted.The final slope stability design involved pattern bolting to thicken the slab and pattern horizontal drain holes to relieve water pressures.

Syncrude Canada Ltd.

The largest mining operation in North America, in terms of volume mined, is the Syncrude tarsands project at Fort McMurray, Alberta. For over 20 years, 90 cu. yd. draglines have mined below an operating bench to a depth of over 150 feet.

The host sands were deposited in a marine river deltaic environment. Clay interbeds were deposited during low flow periods. Along the flow channels, clay layers were deposited at slopes of up to 18 - 20°. Some of the clays have high liquid limits.

The clay layers underlie the dragline bench at varying depths. Where they dipped out of the slope in excess of about 8°, the potential of block failures under the dragline existed. The vibrations and weight of the dragline increased pore water pressures under the dragline pad and shoes, further reducing shear strength.

In order to locate potential unstable areas, a special small-diameter geophysical tool, a dipmeter, comprising four resistivity probes at 90°, was developed jointly by Syncrude and Schlumberger, to locate this unstable geotechnical anomaly in advance of mining. The dipmeter determines the dip and dip direction of clay layers down to about 0.25 inches thick.

Where shallow beds dipping out of the slope were located, they were dug out and backfilled. Where the unstable bedding existed near mid-slope, the beds were broken up by special blasting. Where the unstable beds existed at depth, the dragline placed a stabilizing berm at the toe.

To monitor stability of the dragline slope, geologists walk around the dragline looking for cracks, and slope indicator installations monitor movement at depth. Critical rates of movement have been established which dictate dragline walkoff. Recently GPS (Global Position System) monitoring from satellites, monitor movements to 5 mm accuracy.

The original Geotechnical Review Board in 1972 recommended Syncrude allow for one slope failure which involved a dragline every 10 years for financial costing. Many slides have occurred but only one has really endangered a dragline (fig. 6) and none have been lost.

Steep Rock Mines, Ontario

Steep Rock Mines at Atikokan, Ontario developed a major tension crack in the highwall below the local Algoma Central Railway. The pit slope was about 800 feet high. Mine planning had fallen behind and the only ore available was located at the toe of the highwall.

The author recommended a monitoring program for the slope, and mining be allowed to continue as long as movement was less than 1 inch per day. Prior to continuing mining, all open pit staff were assembled in a large hall. The mine and monitoring approach (first used at Chuquicamata, Chile, (Kennedy, 1970) was described to all. The monitor stations, comprising wire extensometers, were connected to limit switches. If the movement exceeded 0.5 inches in an 8-hour shift, warning sirens and flashing lights were set off. All personnel in the pit were to leave their equipment

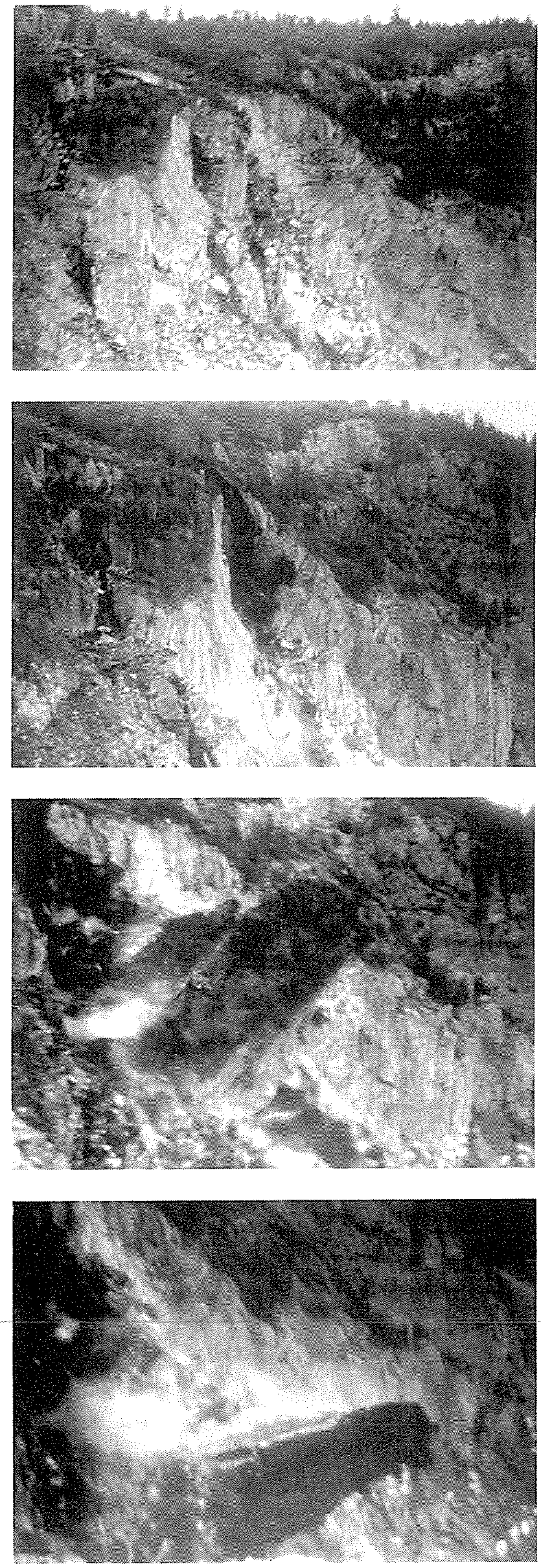

Fig. 7. Sequential toppling failure of an 800-foot highwall at Steep Rock Mine. Monitoring of the slope movement allowed mining to continue until all ore at the toe was removed. After mining was completed, movement accelerated. The date of the failure was predicted.

and "walk" beyond a marked "green" line 800 feet from the toe of the slope. The mine personnel were asked by a show of hands if they would continue to work. All hands went up!

One day during mining, a monitoring technician accidentally slipped and fell over one of the extensometer wires setting off the warning system. One observer recounted, "About 40 pit staff broke the record for the 200-yard dash!"

For three months movement averaged about 0.5 inches per day. During this time mining continued successfully and safely until new ore zones were exposed.

The next spring the movement increased to a point where failure was predicted the day before collapse. All mining equipment had been removed from the area. Sequential failure is shown in fig. 7.

This example illustrates the importance of monitoring slope movement once it develops. Where large volumes are involved (greater than about 500,000 cu. yds.) movements are generally slow and gradually accelerate with time. With reliable monitoring, failure is predictable. If no failures of the open pit slopes have occurred, the slopes are over-designed!

With the development of monitoring of pit slope movement, the safety factor for pit slope design has been reduced to 1.2 to 1.3. Pit slope design with a classical S.F. of 1.5 would sterilize many mining projects around the world.

Spoil-Pile Stability

For every ton of ore mined, one to ten tons of waste rock is usually produced. The ore and waste are separated in the mine, based on ore grade determinations taken on blast hole drill cuttings. The waste rock ranges in gradation from fines to blasted rock up to about 1 cu. yd. The quality of rock ranges from weak, weathered or altered to very hard igneous rock. In coal mining the waste rock varies from soft to hard siltstone and sandstone to bentonitic to hard shales.

To reduce hauling costs, the waste is deposited as close as practically possible to the open pit. As a result, sites may be chosen where foundation conditions are unfavorable. In the mountains of B.C. and Alberta waste piles are often developed on steep mountain slopes, toeing out in valley bottoms where organic materials, glacial lake soils or fine grained fluvial outwash is located.

Failures are usually due to excessively rapid dumping, over-stressing toe areas, not removing organic or weak overburden or burying snow or weak clay-type rock which disintegrates. Recently, liquification in fine-grained layers within the spoil piles has been defined as a failure mechanism.

The B.C. Dept. of Mines (1992) has been a leader in developing guidelines for the investigation, analysis, design and construction of spoil piles.

Contributors to these guidelines include David Campbell who developed a double wedge failure analysis, the author who developed the first extensometer monitoring systems and allowable movement guidelines, Dennis Martin who contributed to investigation and design guidelines and Dr. N. Morgenstern who developed the liquification model.

A unique contribution was the development of criteria for flow through rock drains under high spoil piles constructed in minor stream channels.

With the great height involved a number of spectacular failures have occurred. Two such failures are described.

Kaiser Coal

An open pit coal mine was operating near the top of a mountain about 1 mile east of Sparwood, B.C. The waste was dumped over the mountain face and by June 1968 had reached a height of about 800 feet. The toe of the pile was encroaching onto the valley floor where sediments of old glacial Lake Fernie existed. No geotechnical investigation had been performed.

According to an observer who was looking out his front-room window across the river, the toe of the pile started to move, followed by rapid retrogression of cracking up the slope and flowing down the slope (figure 8). The flow took out the interprovincal electric line, crossed the highway, caught one car and killed two people.

An investigation revealed fines had washed down through the pile and developed a low permeability zone at the base of the pile, which did not allow the natural seepage to exit the mountain. As

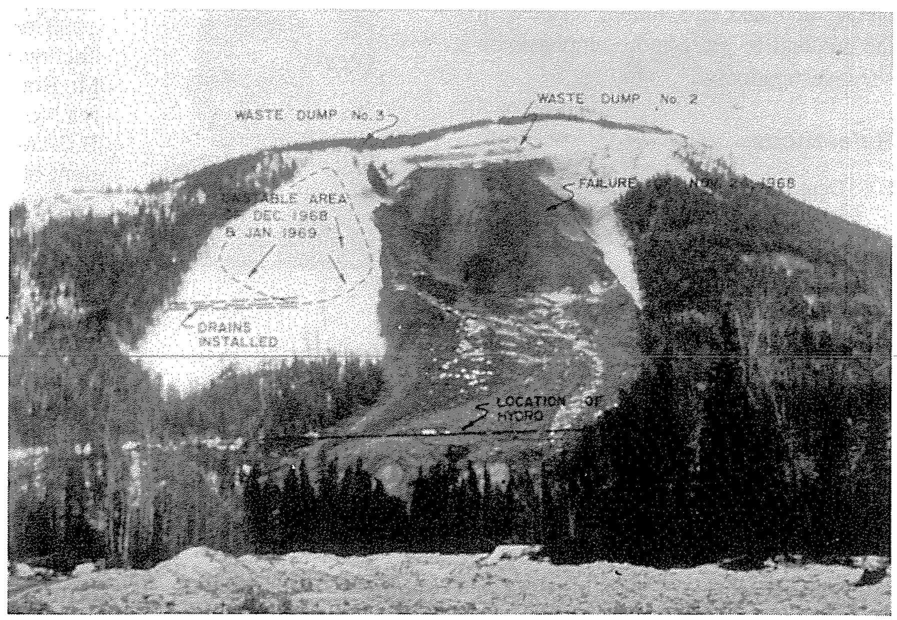

Fig. 8. Spoil pile failure near Sparwood, B.C. The failure developed at the toe which overloaded weak glacial lake soils and retrogressed up the slope. High porewater pressures developed under the pile. The interprovincial electric line and Highway 3 were cut off. Two motorists were killed.

a result, high pore water pressures are believed to have developed under the pile. In addition, the weight of the spoil overloaded the weak toe sediments. As a result of this failure, the provincial Mines Department mandated geotechnical investigations for future spoil piles.

Quintette Coal

A spoil pile was being developed along the flood plain of the Murray River, near Tumbler Ridge, B.C. A geotechnical investigation had been carried out and determined that varved silt and clays comprised the flood plain soils. Based on strength and consolidation testing it was determined by consultants that the spoil must be placed in lifts of nominal thickness and allowed to consolidate, to gain sufficient strength to allow a second lift to be placed. The first lift had been completed and the second lift was in progress. During the night shift a truck driver noted the haul road had disappeared ahead of him. He managed to stop.

After daybreak it became apparent that about 3 million cu. yards of waste rock and floodplain soils had flowed over 1,500 feet toward and into the Murray River, partially damming the river. (fig. 9.)

Subsequent studies indicated the sensitivity of the varved soils was greater and the gain in strength was less than originally calculated.This failure resulted in the demand to place more emphasis on site investigations.

Fig. 9. Failure of a spoil pile on the Murray River flood plain involving about 3 million cu. yds. which partially dammed the river. The weight of the spoil pile overloaded the flood plain sediments.

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Mr. Brawner has had extensive geotechnical and mining experience as a senior materials engineer, B.C. Department of Highways; principal and president of Golder Brawner and Associates, Vancouver; professor of geomechanics of the Mining Department, University of British Columbia; and since 1978 as president of C.O. Brawner Engineering. He is an international authority on the rock mechanics of open pit slopes for mining developments.

Chuck Brawner is the author of over 90 technical papers, an editor of 10 textbooks, a lecturer and keynote speaker, and the recipient of many honours and awards.

Tailings Dams in Canada

Earle J. Klohn

What are Tailings?

Tailings may be defined as the waste product from any number of industries, including mining, mineral beneficiation, manufacturing, chemical processing, etc. Mining, which is one of Canada's leading industries, is by far the largest and most significant producer of tailings. The following comments are limited to mine tailings.

Conventional Mine Tailings

Conventional mine tailings usually consist of the ground-up rock that remains after the mineral values have been removed from the ore. In the case of the oil sands, the tailings consist of the natural soil that remains after the bitumen has been removed. Generally, about 20% of the oil sands' tailings pass a #200 sieve and the remainder are sand sizes.

The grain sizes distribution of tailings depends upon the characteristics of the ore and the mill processes used to concentrate and extract the metal values. A wide range of tailings gradation curves exist for the various mining operations and consequently tailings may range from essentially fine sands to clay-sized material. Fig. 1 illustrates the wide band of gradation curves for different types of tailings.Tailings normally are transported to a nearby disposal area as a slurry, at concentrations varying from 30% to 55% by weight of solids to weight of liquids. The potential pollution hazards associated with storage of the tailings slurry vary with different mining operations, and range from very severe for the radioactive wastes associated with uranium mining, to none for mining processes that merely grind up an inert ore without the addition of toxic chemicals during processing. Between these two extremes there exists a wide range of conditions that represent either short-or long-term potential pollution problems. Most mine tailings fall into this intermediate category.

The tailings disposal area is usually a pond that has been created by the construction of dykes or dams to retain the tailings slurry. The amount of free water stored in the tailings disposal area, together with the tailings, varies from

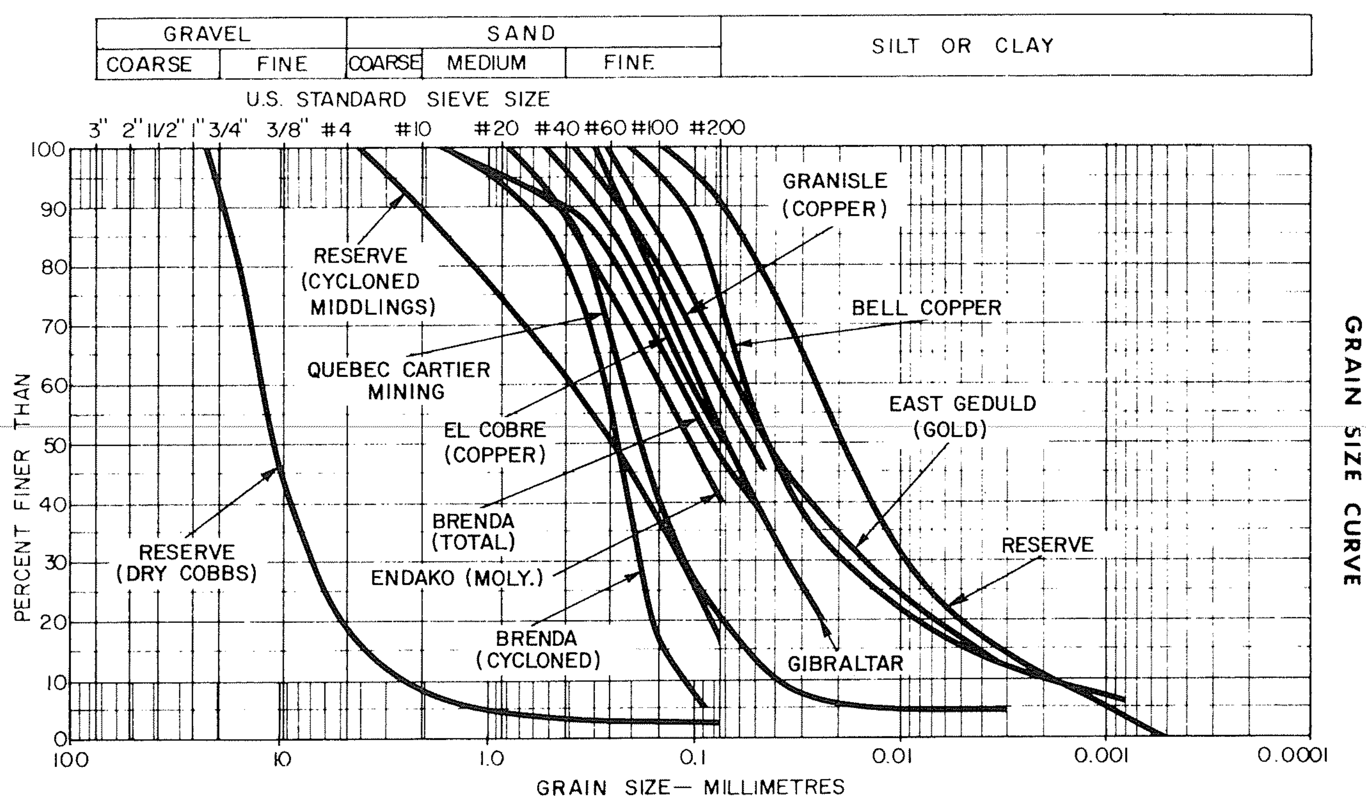


Fig. 1. Typical tailings grain size curves.

very small at mining operations where most of the water is decanted and returned to the mill, to very large for disposal areas that are used for water storage as well as tailings disposal. The volume of free water stored with the tailings has a significant impact on the design requirements of the tailings storage facility.

Canada's Mining Industry

Canadian mining knowledge has been developed through more than 100 years of experience with Canadian mining projects. Many of these projects were typically located in remote areas under very difficult terrain and weather conditions. Successful completion of these projects has required the development of specialized techniques for the exploration, mining and processing of mineral deposits. These specialized techniques have found wide application in many countries around the world. Consequently, Canada has become a world leader in mining exploration and mine development techniques.

In Canada, large mining projects are located in almost every province and territory, with Ontario and British Columbia being the two major areas of mining activity. In British Columbia very large, low-grade, open-pit copper mines have been developed in recent years. These mines produce up to 150,000 tons per day of tailings. In Alberta the oil sands represent a very special and unique mining development. TheSyncrudeandSuncor oil sands operations are both large open pit mines, with the Syncrude operation producing up to 250,000 tons per day of tailings.

These large open-pit operations require the safe storage of huge volumes of tailings. Canadian engineers have responded to this challenge and have developed the necessary techniques to construct economical tailings dams to safely store these enormous volumes of tailings. These "made in Canada" tailings dam design and construction techniques are currently being exported around the world by several Canadian consulting engineering companies.

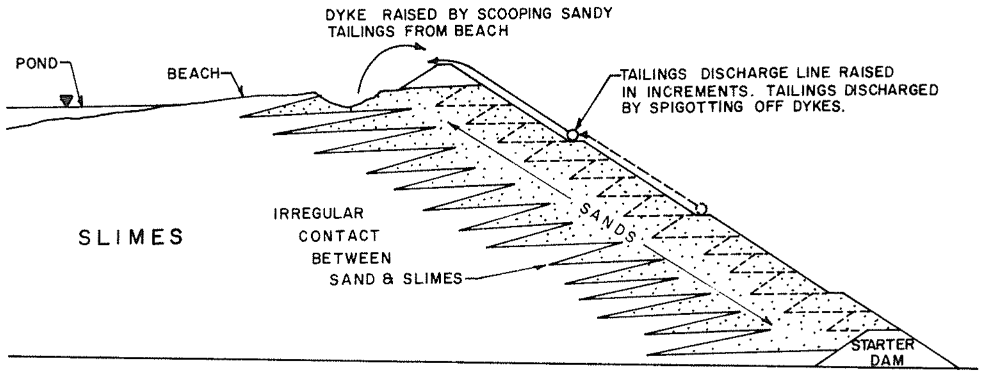


Fig. 2. Upstream method of tailings dam construction.

Fig. 3. Upstream dam construction, Hollinger Mine, Ontario (1936)
(National Archives of Canada PA 017613).

Evolution of Current Tailings Dam Designs

As tailings are a waste product of the mining industry, there has always been pressure to find the most economical method of disposal. In the early days of mining, only ores of the highest grade could be economically mined and consequently very small volumes of waste were produced. As mining and milling methods improved, lower grade ores became profitable to mine and the volumes of tailings produced became greater. The initial methods of disposal involved dumping the waste tailings at the nearest convenient location, where they were slowly eroded by wind and water, often ending up in streams where they were washed away. In some instances these early tailings were dumped directly into streams and lakes, which provided a very convenient and economic method of disposal. The early mines were usually located in remote areas that were generally uninhabited and contained little or no agricultural development.

These early mines were very small by today's standards and produced tailings volumes ranging from a few hundred to a maximum of a few thousand tons per day. Nonetheless, as towns and agricultural development began to grow in these mining areas, conflicts began to develop concerning pollution of streams and contamination of crops and grazing lands. The conflicts resulted in the end of the uncontrolled dumping of tailings and gave rise in Canada, in the early part of this century, to the construction of the first tailings dams.

The miners of these early days devised a procedure for building tailings-impounding structures that utilized a minimum of fill placement. This was achieved by building a low starter dyke and discharging tailings from the top of the dyke until the impoundment was filled with tailings. Then using these tailings, a second small dyke was constructed and the procedure repeated, so that the tailings dam slowly rose in an upstream direction on top of the previously deposited tailings. This method, which has become known as the "upstream method" of tailings dams construction, is illustrated in fig. 2. Figs. 3 and 4 are photographs of some early tailings dams being constructed by this method.

Many tailings dams have been constructed using the upstream method of construction and the majority of these structures have performed satisfactorily. However, failures were not uncommon, and following the major failures that occurred at the El Cobre dams in Chile[1] during an earthquake and many less dramatic failures under static loading conditions, it became obvious that improvement to the original upstream construction methods were necessary. This resulted in the development of the "downstream" and "centreline" methods of construction. These new construction methods involve raising the tailings dam by continuous construction in a downstream direction on top of engineered fill and previously prepared foundations. Figs. 5 and 6 illustrate these two methods of construction.

In the last thirty years, very large open-pit mining operations have come into production in Canada. These operations, which have been made possible by the development of very large and efficient earth and rock moving equipment, produce huge vol-

Fig. 4. Upstream dam construction, B.C. (Early 1950).

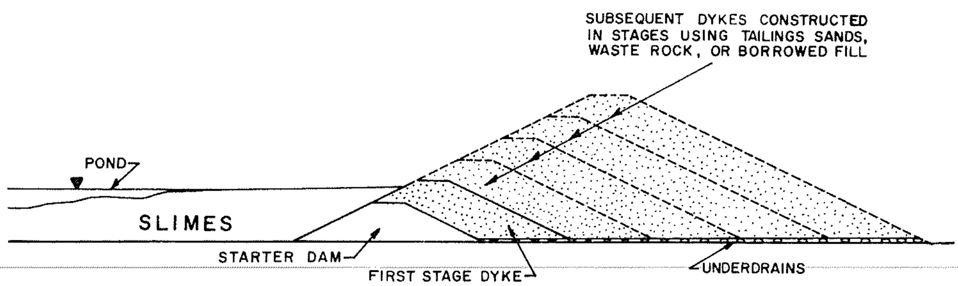


Fig. 5. Downstream method of tailings dam construction.

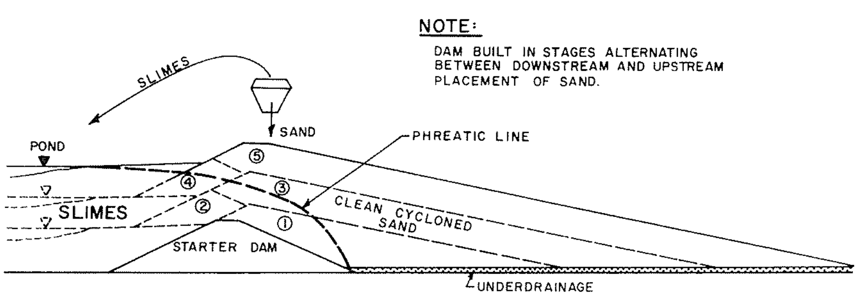


Fig. 6. Centreline method of tailings dam construction using cycloned sand.

umes of tailings. Open-pit metal mines producing 100,000 to 150,000 tons per day of tailings are not uncommon. However the largest open-pit mining operations are in the Alberta Oil Sands, where approximately 250,000 tons per day of tailings are produced at the Syncrude operation. To meet these huge storage demands, tailings dams have evolved into very large, critical, hydraulic structures that pose similar dam safety problems to those posed by major conventional water-storage dams. In fact, tailings dams now rank amongst the world's largest dam structures. Developing suitable design and construction techniques, to ensure that these very large tailings dams can be safely constructed and operated, has presented a range of challenging problems. Canadian engineers have successfully met this challenge and are now exporting their tailings dam designing experience to many countries around the world.

Current Tailings Dam Design Practice

Most large tailings dams are built in two stages. Stage I, the initial starter dam, is constructed before the mining operation starts and provides the starting point for construction of the ultimate tailings dam. The type of starter dam selected depends on the method of construction to be used for the remainder of the tailings dam.

For example, where downstream methods of construction are proposed, the starter dam may be constructed as a conventional water storage dam and be used to store mill start-up water. On the other hand, where upstream methods of construction are proposed, the starter dam may be constructed as a pervious drain to control the phreatic surface in the ultimate tailings dam.

Stage II involves the construction of the remainder of the tailings dam. This phase of construction, which is carried out by the mining operators, constitutes the major portion of tailings dam construction. Stage II construction is a continuous operation, which begins with the start-up of mining operations and continues until mining operations cease, or the tailings pond is filled.

Upstream Construction Methods - in the past, practically all tailings dams were constructed by some variation of the "upstream method" of construction. The original upstream construction procedures, where the dam was raised by building each new dyke over top of the previously deposited tailings, have been successfully used in arid climates, where evaporation losses are high and a minimum of water is stored in the pond. Under these conditions, the phreatic line through the tailings dam is low, some chemical cementing of the dried-out tailings may occur, and, provided sufficiently flat outer slopes are used, relatively high tailings dams can be successfully constructed under static loading conditions. However, under severe earthquake loading conditions, liquefaction may occur causing the dam to fail.

In more recent times, modified versions of the original upstream method of construction have evolved that include such design features as:

- providing wide sand beaches between the tailings dam and the pond;
- compacting a portion of the sand beach upstream of the starter dam so that it cannot liquefy;
- providing extensive drainage upstream of the dam to maintain a low phreatic line; and,
- providing flat downstream slopes for the tailings dam.

By combining one or more of these features, tailings dams can be constructed using upstream construction procedures, to safely withstand earthquake forces. Two major projects currently under construction in Canada that use "upstream methods" of construction, utilizing some of these design features, are the Syncrude tailings dams[2] and the Inco Sudbury tailings dams[3].

Downstream Construction Methods - over the past 25 years, a significant number of large tailings dams have been constructed using "downstream methods" of construction. The major advantages of the downstream method of construction are:

a) The foundation for the dam can be prepared as required, with none of the embankment built on top of previously deposited tailings;
b) The fill operations (placement and compaction) can be controlled to achieve whatever degree of density is required.
c) The underdrainage and internal drainage systems can be installed as required as the dam is built. The drainage systems permit control of the phreatic surface through the dam.

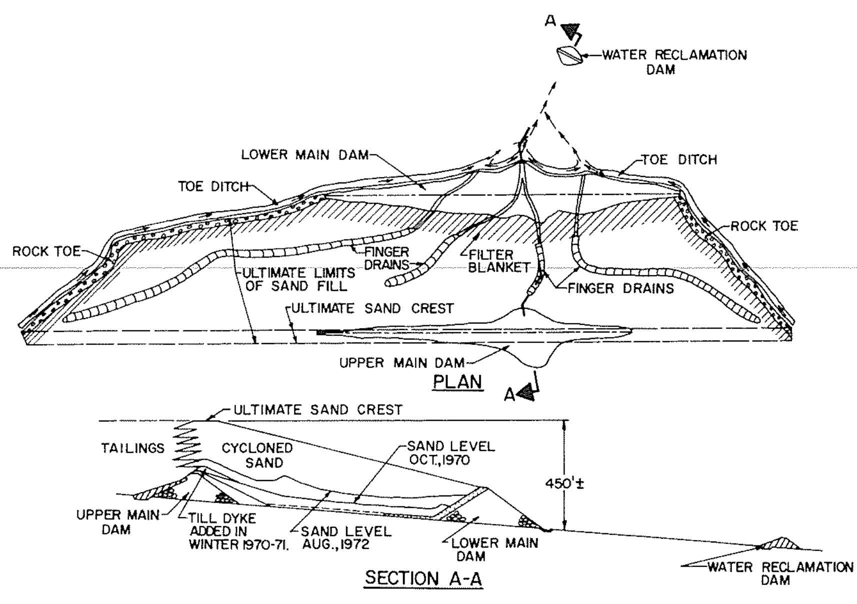


Fig. 7. Plan and section through Brenda Mines tailings dam.

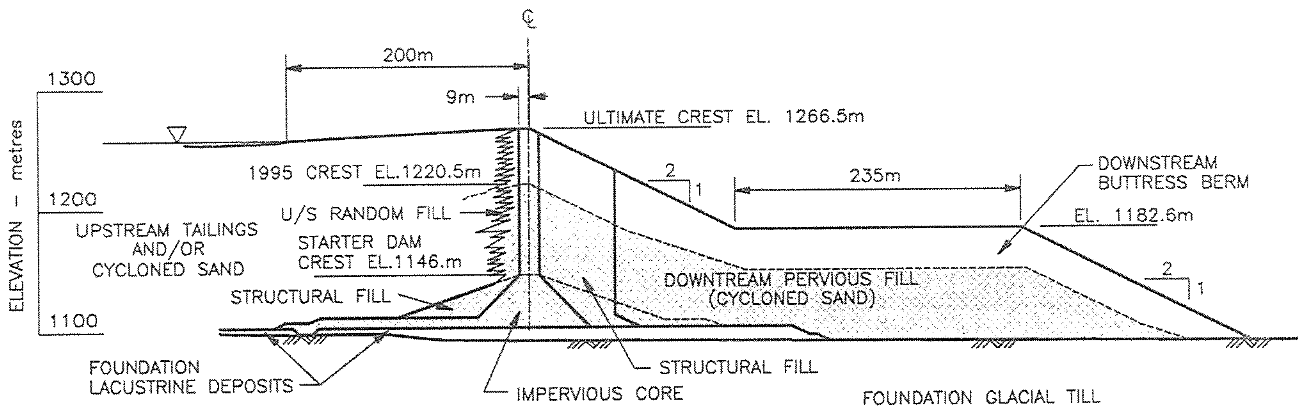


Fig. 8. L-L Dam Typical valley section Highland Valley Copper Mine.

Fig. 9. Photo looking along downstream scope of L-L Tailings Dam, Highland Valley Copper Mine.

d) The dam can be designed and subsequently constructed to whatever degree of competency that may be required, including resistance to major earthquakes.

Two major British Columbia tailings dams built by the downstream method are Brenda Mines[3] and Highland Valley Copper[4].

In a few instances major tailings dams have been constructed using open-pit waste or nearby borrow materials. Some mining developments produce large volumes of overburden and rock from the open-pit stripping operation. Where this is the case, consideration should always be given to utilizing these materials for construction of the tailings dam.

Examples of Current Designs

Tailings dam design is site specific and varies from project to project depending on such items as foundation conditions, topography, hydrology, seismicity, physical and chemical properties of the tailings, availability of construction materials, and volumes of tailings to be stored.

Three examples of current tailings dam designs are presented following. Two of these examples (Brenda Mines and Highland Valley Copper Mines) utilize the downstream method of construction. The third example (Inco R-4) utilizes a modified version of the upstream method of construction.

Brenda Mines - the Brenda tailings dam is an example of a large tailings dam, constructed from cycloned tailings sand, using the centreline method of construction. The mine, which is located in the Okanagan region of B.C., started operations in 1967 and was closed in 1990. Rehabilitation operations are currently under way. The dam reached an ultimate height of about 137 m with a crest length of about 1,600 m. A plan and section through the dam are presented in figure 7.

Highland Valley Copper - Highland Valley Copper, which is located in the Kamloops, B.C. region operates a very large open-pit mine, which results in the production of approximately 133,000 tons per day of tailings. To store these large volumes of tailings, will require raising the main dam to an ultimate height of approximately 169 m. The length of the ultimate dam, as measured along its crest is about 3,000 m. The dam is currently (1997) about 125 m high, with a crest length of 2,300 m.

The dam has a compacted downstream shell composed of cycloned tailings sand and granular borrow materials. The upstream shell is cycloned sand and the tailings beach. The dam has a central impervious core. A section through the dam is presented in figure 8. Photos of the Highland Valley Copper Tailings Dam are presented in figures 9 and 10.

Inco - Sudbury Operations - Inco operates several large tailings ponds at their Sudbury operations. The newest development, called the R-4 area, is currently under construction.

Where peats and soft clays are encountered, they are removed from an area encompassing the base of the starter dam and extending approximately 92 m upstream. The excavated area is then backfilled with quarried rockfill to provide a stable base for the ultimate dam. Finger drains, on 23 m centres, extend from the centreline of the starter dam to 37 m upstream of the centreline. The dam itself is constructed in the upstream direction by spigotting off a wide (153 m) beach. The inner 92 m of the beach is compacted as it is placed by tracking bulldozers.

Figure 11 presents a section through a typical R-4 tailings dam. The flat downstream slope and the compacted upstream tailings, combined with the low phreatic surface, provide a tailings dam that can safely withstand the maximum creditable earthquake (M.C.E.) for the area. The wide beach, the relatively pervious compacted sand zone, and the upstream underdrainage system all contribute to maintaining the low phreatic surface.

Safety of Tailings Dams

The problems associated with the safe storage of tailings have become greater, as rates of production have increased and mining operations have come into much closer contact with inhabited areas. Currently under construction, are tailings dams that will have ultimate heights approaching 200 m. Obviously, tailings dams such as these are critically important hydraulic structures, whose safety must be assured both during mining operations and after mining operations have ceased.

There are two basic items to be considered when addressing the problem of "safety" for tailings dams. The first item is the structural stability of the embankment against failure by such mechanisms as: liquefaction, sliding, slumping, overtopping, piping, etc. Should a major tailings dam fail, a very large volume of water and semi-fluid tailings would be discharged downstream. Such an event, not only would pose a serious threat to life and property, but also would cause extensive downstream pollution.

The second item relates to the safe containment of any toxic materials in the tailings pond. Obviously, the structural stability of the embankment could be perfectly satisfactory, but toxic materials could still escape from the tailings pond through, or under, or around the tailings dam and into the streams and groundwater of the area. This problem must be prevented both during the operating life of the mine and/or after the mining operations have ceased.

Evaluation of the safety of tailings dams therefore may be conveniently divided into two separate items as follows:

i) Structural Stability of Dam: covers the physical safety of the embankment and related structures.

Fig. 10. Aerial view of L-L Tailings Dam Highland Valley Copper Mine.

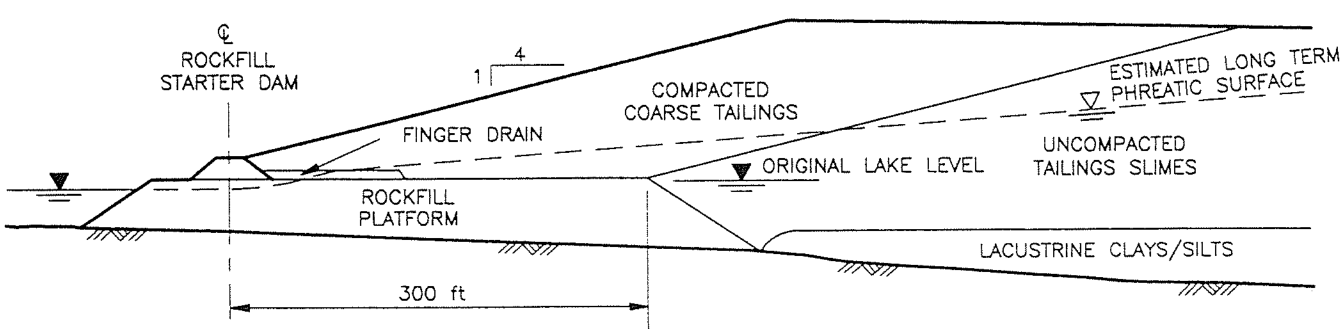


Fig. 11. Inco R-4 Sudbury, Ontario - typical dam section.

ii) Environmental Safety: covers all aspects of storing toxic and radioactive materials without creating unacceptable levels of environmental damage.

The first item "Structural Stability" is the item that comes to most engineers' minds when tailings dam safety issues are raised. The second item, however, is becoming increasingly important as society becomes more and more aware of the problems associated with environmental damage. Reviewing the physical safety of a tailings dam is a relatively straightforward exercise, provided that all of the required basic data are available. For new designs, this is usually the case with the data obtained from the installed instrumentation providing the required check on whether or not the dam is performing as designed. For existing older tailings dams, the task may be much more difficult if records are missing concerning the original basis of design, construction methods, or performance monitoring data.

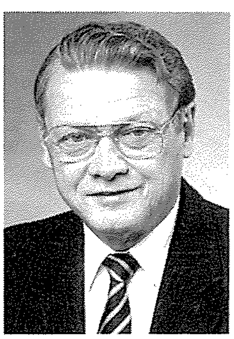
Ensuring the "Environmental Safety" of a tailings dam usually has an important bearing on the dam's design and construction. The tailings dam may be safe physically, but the impoundment may be losing pollutants, by seepage through the base and sides of the pond, through the dam abutments, through the dam foundations, or through the embankment itself. Moreover, seepage losses which are not considered to pollute the surface and groundwater initially, may become pollutants with the passage of time. Obviously the entire area of environmental safety poses a special problem that is site specific, as it depends not only on the imperviousness of the pond and dam, but also on the physical properties of the tailings and the re-agents used in the milling process.

Consequently assessing the environmental safety of a given tailings facility requires knowledge of physicochemical and chemical reactions as well as seepage flows and groundwater movements. Good tailings dam design-practice requires that both the "Structural Stability" and the "Environmental Safety" are carefully addressed in the initial designs.

Conclusions

The development of very large open pit mining operations in Canada in recent years has produced new challenges for tailings dam designers. These new mines produce huge volumes of tailings, which often require very large tailings dams to provide the necessary storage capacity. Tailings dams, with heights approaching 200 m, are currently under construction. These are major hydraulic structures that pose similar dam safety problems to those posed by large conventional water storage dams.

Canadian engineers have successfully met the challenge of developing tailings dam designs that satisfy both the "Structural Stability" and "Environmental Safety" requirements of these major hydraulic structures. The expertise developed, through the experience gained from designing these Canadian tailings dams, is being successfully exported by several Canadian engineering firms to many countries around the world. Thus Canadian tailings dam designers have joined their mining engineering colleagues as international exporters of Canadian engineering services.



EARLE J. KLOHN received his civil engineering degrees at the University of Alberta in 1950-52, under professors I.F. Morrison and R. M. Hardy. Klohn is a geotechnical engineer with 45 yerars of consulting experience. He joined Ripley and Associates in 1952, became president of Ripley, Klohn & Leonoff in 1970 and is president and CEO of the successor firm, Klohn-Crippen Consultants. He has had extensive experience in the design and construction of earthfill and rockfill dams, and heavy industrial foundations. He has served on numerous review boards for both conventional water storage and tailings storage dams and is recognized internationally for tailings dam design. Mr. Klohn has authored more than 60 technical papers, has participated in several technical and professional organizations, and is the recipient of many honours and awards. He is a past chairman of the Vancouver Geotechnical Society and a past president of the Canadian National Committee on Large Dams (CANCOLD).

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Interpreting Airphotos and Analyzing Terrain for Engineering and Geoscience Projects: 50 Years of Memories

Jack D. Mollard

Where, When and How It All Began

My memories of airphoto interpretation and terrain analysis for geotechnical and geoscience applications go back to the fall of 1945 when I enrolled in a master's degree program in civil engineering at Purdue University. Just then innovative engineering geologist Professor Donald Belcher was setting up his first course in airphoto interpretation, also called airborne remote sensing, and a new field of specialization closely allied to geotechnical engineering and engineering geology, and I signed up for it.

I was drawn to Belcher's prowess in the military and civilian applications of airphoto interpretation and terrain evaluation. His research on the origin, distribution and airphoto identification of United States soils lead to a federal Civil Aeronautics Administration contract in 1943, to identify 15 airfield sites to train airforce pilots and later serve as municipal airports. In 1944 Belcher's expertise caught the personal attention of General Douglas MacArthur, who flew him to the Southeast Pacific to locate airfields and roads in tropical jungle. In 1945 the Army switched Belcher to Alaska; and my first photointerpretation assignment was to help him locate airfield sites that avoided thaw-sensitive permafrost.

I soon became fascinated by the analysis of terrain from stereoscopic airphotos, and by the quest for diagnostic clues to the kinds and conditions of soils and rocks that lay hidden beneath the earth's surface. So began a 50-year career in airphoto interpretation and terrain analysis in engineering, which increasingly involved applications in the geosciences, and eventually in the life sciences.

Dr. Karl Terzaghi of Harvard University, visiting lecturer at Illinois University, heard about Belcher's pioneering studies and wanted to know more about them and how they might contribute to the practices of soil mechanics and engineering geology. Dr. Ralph Peck at the University of Illinois offered to drive Terzaghi to Purdue. Quickly the art and science of airphoto interpretation spread from Purdue to the universities at Harvard and Illinois then to New Jersey, Ohio and others in the late 1940s and early '50s.

Belcher left Purdue in 1946 to accept a position at Cornell University, where he set up the Centre for Airphoto Interpretation Studies. His research and teaching there from 1946 to 1976 influenced students from a dozen countries and attracted students from the engineering, geology, agriculture, forestry, and urban and regional planning faculties.

Robert Frost, Belcher's research assistant at Purdue, succeeded him as my major professor. And for over 50 years Frost taught, practised and promoted the interdisciplinary interpretation of airphotos as an aid to developing natural resources and planning engineering projects, with minimal upset to the environment.

Both Belcher and Frost had been influenced by Tom Bushnell, a visionary soil scientist at the Agricultural Experiment Station at Purdue. Some say Tom first noticed soil patterns from the air while flying over France in a balloon during World War I. It is true that as early as 1926 he started taking his own airphotos and interpreting soil landscape patterns and in 1938 was probably the first in North America to publish vertical airphotos illustrating 14 diverse soil patterns, reflecting the geologic processes and genetic factors that created them. Yet I consider Don Belcher and Bob Frost the founders and early proponents of applied airphoto interpretation and terrain analysis in civil engineering and engineering geology. At Purdue I had the

Photo 1. Geological reconnaissance, at dusk, along the Mahawel Ganga valley, Ceylon, 1956.

good fortune of being in the first class Belcher taught, and also in Frost's. I was also Frost's first postgraduate student specializing in airphoto interpretation and terrain analysis.

Pioneering Airphoto Interpretation and Terrain Analysis in PFRA

I returned to Regina in April 1947 to work for the Prairie Farm Rehabilitation Administration (PFRA), a federal soil and water rehabilitation and conservation agency. At that time, recent geotechnical graduates with PFRA's Soil Mechanics and Foundation Division were investigating earth dams and irrigation projects on the Canadian Prairies and carving out an international reputation.

PFRA had a large and growing library of aerial photographs, but no one to interpret them. My first assignment was to help locate a major damsite, eventually Gardiner, along the slide-prone South Saskatchewan River valley. At first I had difficulty convincing my colleagues that many gentle bumpy slopes along that valley were landslides in bentonitic shale, not hummocky moraines. In the following years the cause and behavior of these slides, and their identifying characteristics in 3-D airphotos, were discussed at length in meetings with PFRA's board of dam consultants.[1]

I treasured these meetings, enjoying discussions of geological events and their dam foundation implications with Bob Peterson, Charlie Ripley and other geotechnical engineers in PFRA, geological consultant Professor John Allan, University of Alberta, and geotechnical consultants professors Arthur Casagrande and Karl Terzaghi, Harvard University. Terzaghi was interested in my photo interpretation and engineering geology studies, and invited me to lecture at Harvard in 1953.

My airphoto and geology studies at Gardiner were the first of more than 60 dam sites, the majority located in the Saskatchewan-Nelson basin and the Columbia and Fraser basins in British Columbia. Finding a stable hydro site on Kodiak Island, Alaska, in 1965 stands out because of the devastating effects of the catastrophic 1964 Anchorage earthquake and giant tsunami, lifting buildings in Kodiak town, and triggering slides in thick ash from a 1912 volcanic eruption in the Valley of Ten Thousand Smokes.

Further Studies at Cornell

I went to Cornell University in January 1950 to take a Ph.D. under Professor Belcher. Because of my work at PFRA, he agreed to let me take nearly all of my postgraduate courses in geology and geotechnical engi-

Photo 2. Which way to the gravel? Rettie (glasses) and Mollard (toque), northern Manitoba, 1957.

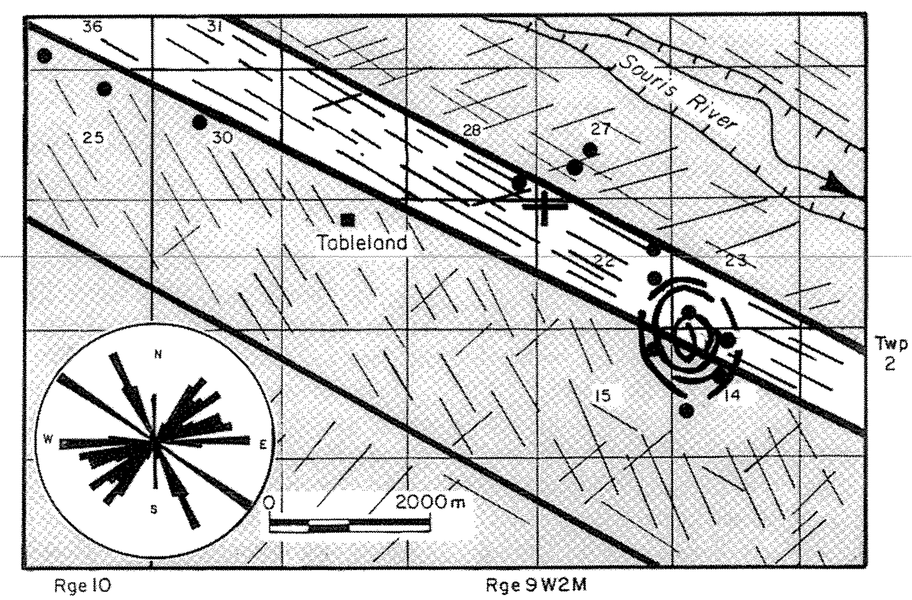


Fig. 3. Tracing of an extraordinary photolineament pattern that raised speculation about deep geologic structures and prospective oil targets, 1957.

neering. I took additional courses in soil genesis, morphology and soil mapping in the Agronomy Department. That mix of postgraduate courses and Belcher and Frost's interdisciplinary approach to airphoto terrain analysis had a profound influence on my career.

At Cornell I was excited to learn that I would be assisting Belcher, who had airphoto interpretation contracts to detect World War II land mines in western Europe, locate diamond pipes in South Africa, find placer gold in California, and discover oil-trapping salt domes along the Gulf Coast of Texas and Louisiana—in addition to locating highways, airfields, pipelines and waste disposal sites. All entailed three-dimensional evaluation of terrain from the regional perspective provided by conventional airphotos. We were either seeking some desired target, often elusive and unnoticed on the ground, or avoiding terrain that would be hazardous, environmentally sensitive, or costly to build on.

Spreading the Word

If remote sensing of terrain were to develop in Canada, I thought it had to be widely applied in engineering and the geosciences, and began spreading the word. Over the next 45 years I gave 75 short courses and workshops to over 3,000 multidisciplinary participants, and published more than 100 papers and articles in technical and professional journals and two books. My first paper, presented at the third Canadian Geotechnical Conference in Lethbridge in 1949, was titled "The Application of Airphoto Analysis to the Determination of Soil Conditions." It was followed later that year by "The Airphoto Interpretation of Transported Soil Materials," published in the *Engineering Institute of Canada Journal*, for which I received the EIC's Keefer Medal.

I lectured in Belcher's courses at Cornell in 1952, at Harvard in 1953 and 1958, and from 1959 to 1995 I ran short courses organized by the Extension Department, University of Alberta. During the first 12 years I lugged over 5,000 airphotos to class for interactive terrain analysis by up to 60 attendees, classifying and separating the airphotos into nine terrains: bedrock, glaciated, slope movements, running water, groundwater, coasts and shorelines, wind, peatlands, and permafrost and ice. I carried the airphotos in nine wooden boxes totalling 630 pounds. Then in 1972 Professor Karl Sauer asked me to put together a 680 stereogram airphoto atlas of landforms and surface materials of Canada, which I used in courses for the next 24 years.

My first short course at the University of Alberta was sponsored by professors Bob Hardy in civil engineering, Robert Folinsbee in geology, and Arleigh Laycock in geography. Major J.L. Charles, retired Chief Engineer of the CNR in Winnipeg, and Roger Brown and Hank Johnston, Permafrost Section, National Research Council, Ottawa, were participants. A 1961 course in Regina was attended by John Gartner, Bill Jubien, Barry Mickelborough, George Mollard, and Karl Sauer.

I always said I took away more from my courses than those taking them. Engineers and geologists added firsthand knowledge and information on many of the landscapes analyzed interactively in class. I was fortunate to have Charlie Ripley and Mark Olsen of Ripley Klohn Leonoff, Harold Morrison of R.M. Hardy and Associates, and Murray Harris of Thurber Consultants in courses. All three principals in Bruce Geotechnical Consultants—Iain Bruce, Wayne Savigny, Bob Tape—enrolled in these short courses, as did several other postgraduate students of professors Morgenstern, Thomson and Cruden, between 1968 and 1980, and many specializing in permafrost and landslide investigations.

A particularly memorable series of cross-Canada multidisciplinary courses was given to Canada Land Inventory mapmakers, carrying out a national mapping program that began in 1963 and lasted for 15 years, culminating in land capability maps for agriculture, forestry, ungulates, waterfowl and recreation.

A week-long course at the University of Hawaii in 1967 presented an opportunity to illustrate two applications of thermal infrared imagery analysis: monitoring the thermal profiles of active volcanoes on the Big Island, and identifying plumes of cool groundwater discharging into warm ocean water on Oahu, where along the coast several hundred metres of fresh groundwater floats on denser salt water.

Photo 4. Interpreting airphotos inside an Inuit tent, Union River, Somerset Island, 1976.

I was always pleased when someone in my short courses went on to teach at colleges and universities. Professor Karl Sauer is one of them. He introduced his first airphoto course to graduate students at the University of Saskatchewan in 1968 and to undergraduates in 1973. In 1982 he developed a self-learning booklet that led students step-by-step through each stereogram in my *Landforms and Surface Materials in Canada: A Stereoscopic Airphoto Atlas and Glossary*. Typically, 70 to 80 students from several faculties and colleges—engineering, geology, geography, biology, archaeology, agriculture, environmental sciences—sign up for his class, one of the most sought after on campus, which he calls "Evaluation of the Physical Environment."

Space Imagery Remote Sensing

Today's remote sensing practitioners have access to a wide selection of airphoto and satellite imagery products. Since 1972 we have purchased more than 600 satellite images as well as thermal, infrared and radar imagery to support remote sensing from conventional and infrared airphotos. And yet, with all the outstanding advancements in space imagery technology, for most engineering projects it is necessary to obtain good quality multidate, multiscale stereoscopic aerial photographs, in order to interpret the finer—and often essential—diagnostic terrain detail.

Memorable Projects and Unforgettable Experiences

I've had many interesting projects and experiences, some memorable, some quite unforgettable.

In 1953, I was seconded from PFRA to the Shaw Royal Commission on Newfoundland Agriculture, to map that island's soil and terrain. A year later I was seconded to the Canadian Colombo Plan Project to serve as technical adviser on an aerial resource survey of West Pakistan, then of Ceylon (now Sri Lanka).[1]

On the return flight from a 1956 trip to advise on these airphoto mapping projects, a large turkey buzzard struck and crippled our aircraft as it was taking off over the Bay of Bengal. The buzzard damaged one wing of the plane before glancing off my window. I spent the next three days in Rangoon, Burma (now Myanmar), waiting for another plane. Here I had the good fortune to meet Tom Bushnell, now retired from Purdue and consulting overseas. He described his early airphoto studies of Indiana soils, and the letters he sent to federal Secretary of Agriculture Henry Wallace, urging the government to take airphotos, to cut the cost of soil mapping and improve its accuracy and reliability.

In February 1956 I left PFRA's Airphoto Interpretation and Engineering Geology Division in the capable hands of Don Pollock, and opened a private consulting practice in Regina.

My children often said that I never met a gravel prospect I didn't like, and I've identified many thousands of them. I won't forget the one I mapped for Con Smythe while waiting in Toronto to fly to Karachi. Years later I was told that Mr. Smythe—of Toronto Maple Leaf Gardens and hockey team fame—bought the land, removed the gravel I had located, and sold the property to real estate developers.

In February 1957 Jim Rettie, Chief Engineer at Manitoba Hydro, contacted me in Los Angeles where I was advising Fairchild Aerial Surveys on the interpretation of large oil-bearing fold and fault structures in Khuzistan, Iran. Jim wanted me at a remote siding on the Churchill railway, within two days, to look for gravel deposits I had previously identified to construct a 20-kilometre stub rail line to the new Kelsey power generating station. I flew to Regina, picked up airphotos and winter gear and headed out, catching a small ski plane at Lac du Bonnet northeast of Winnipeg. We landed on a small frozen lake covered by giant snow dunes, shot over the steep lee slope and dropped several metres into minus 40 temperatures. I spent the next three nights sleeping in an unheated boxcar with all my clothes on: toque, heavy boots, and all—and the daylight hours trying to find gravel under a metre and more of snow.[2]

No other consulting project has been more rewarding than discovering groundwater for Prairie towns and villages. We searched for, found, installed, tested and evaluated over 100 municipal water wells. Many a senior citizen, whose only water was hauled in barrels, often by a team of draft horses in minus 40 degree weather, described the joy they felt having the convenience of running water and flush toilets.

In 1957 I marked a cross on an airphoto for an article in the July *Canadian*

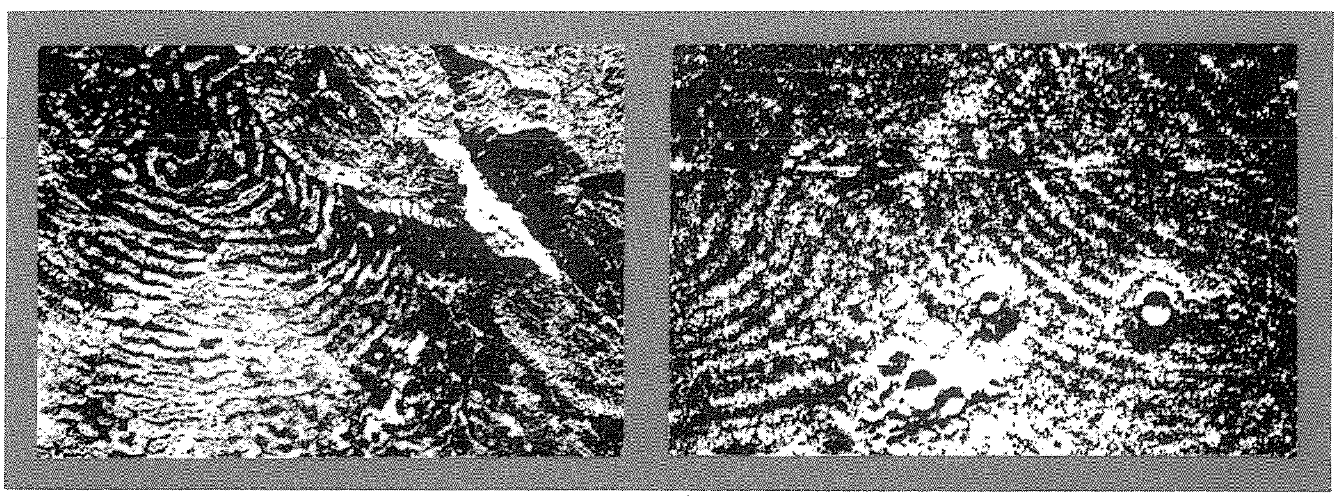


Photo 5. Look-alike enigmatic thumbprint patterns in northern Alberta (left) and on Mars, 1994.

Oil and Gas Industries journal. I conjectured that an extraordinary airphoto lineament pattern might somehow be tectonically inherited, and therefore related to oil-bearing structures at depth. At 11 p.m. on February 25, 1986, I was awakened by Stuart Jordan, consulting oil geologist, phoning from Estevan to say that drillers had just struck a large oil-bearing reef 2,600 metres below ground surface—and almost right over the cross I had marked 29 years earlier. That reef and smaller ones along the same photolineament turned into a multimillion dollar oil discovery, and oil companies are still drilling for oil along the same feature.[3]

In 1969 Shannon and Wilson, consulting geotechnical engineers in Seattle, asked me to carry out an airphoto terrain analysis to locate a trans-Alaska rail line, to transport oil from the Arctic Coast south to Valdez. That was the forerunner to 13 years and 30,000 kilometres of airphoto study and terrain mapping of proposed pipeline routes to transport gas south from Prudhoe Bay, Alaska, the Mackenzie Delta and the Arctic Islands. I flew nearly all these routes in a helicopter, often with Don Hayley and client representatives, always serving as navigator and terrain interpreter.

I still recall some trips with horror: being chased across Southern Indian Lake by an irate bald eagle, and being dropped into cold water in Lac La Martre to roll away boulders on the shore of a boulder islet so that our chopper could land to take on fuel with less than a gallon in the tank. And wandering far off-course from over snow-clad tundra in near whiteout to snow-veneered ice on the Arctic Ocean south of Spence Bay, with no sight of land when the fog lifted.

During one memorable trip, Charlie Neill of Northwest Hydraulics and I stopped to assess my pipeline crossing of the Union River on Somerset Island. An Inuit family had moved south from Resolute for the summer to fish that river. They said I had located the pipeline route across their ancestors' graves, indicated on the ground by small piles of stacked rock. So I pulled out the airphotos, studied them in 3-D on the floor of the tent, and together we relocated the pipeline route to avoid the graves.[4]

A few years ago I was asked to speculate on the origin of enigmatic thumbprint patterns appearing on space pictures of Mars. A planetary scientist at the University of Arizona noticed that they resembled thumbprint patterns in my large airphoto atlas, and sent me 28 space images of Mars. Some patterns vaguely resembled whorl-like markings on the corrugated failure scars of lateral spread flowslides in the St. Lawrence Lowlands. However, after seeing another thumbprint pattern in a planetary geology book, I believe the Mars pattern more likely originated from slow downslope creep of melting permafrost in lakebed terrain, such as thought to occur on the upland adjoining the Peace River Valley in Alberta.[5]

I have great memories as I look back 50 years, interpreting airphotos and analyzing terrain on more than 4,000 multidisciplinary projects—memories of looking for gravel and groundwater, gold and oil, better sites and routes, natural and human geohazards and environmental concerns, and recently diamonds and opals. But just as special are the memories of engineers, geologists and others I've met in government, short courses and consulting—and especially the memories of talented individuals I've worked with in a field I still enjoy.

JACK D. MOLLARD was born in Regina and raised on a St. Bernard ranch at Watrous, Saskatchewan. He received a civil engineering degree from the University of Saskatchewan in 1945, then took post-graduate training in geotechnical and highway engineering, geology and airphoto terrain analysis and evaluation at Purdue and Cornell, universities, obtaining his Ph.D. from the latter. In 1995 the University of Regina conferred an honourary Doctor of Laws on him.

For half a century Mollard has pioneered the mapping and evaluation of Canada's physical environment and natural resources from aerial and space imagery.

His research and consulting work have included locating construction materials for road construction across Canada, finding groundwater for prairie towns, selecting townsites and transportation routes in Northern Canada, and Alaska, and prospecting for oil, gold and diamonds. He has worked as a land surveyor, highway construction engineer, research engineer in airborne remote sensing, and an engineering geologist on dams and landslides. Since forming J.D. Mollard and Associates in Regina in 1956, he has consulted on more than 4,000 assignments in Canada, six continents, and on Mars. Mollard has served as a technical advisor to developing countries on multidisciplinary aerial resource surveys.

Dr. Mollard has authored over 100 scientific and technical papers, given two Cross-Canada Distinguished Lecture Tours, and has been a visiting lecturer at several universities in Canada and the United States. He is a fellow of six international scientific and global exploration societies. He has received many awards, among them the Engineering Institute of Canada Keefer Medal (for the best technical paper), the American Society of Photogrammetry and Remote Sensing Award (for pioneering contributions to remote sensing), the Royal Canadian Geographical Society Massey Medal (for exploring, developing, and describing the geography of Canada), the McCannel Award (for technical excellence and engineering achievement) and the Canadian Geotechnical Society Legget Award.

Earthquake Engineering in Canada: A Selective Overview

W.D. Liam Finn

On the fifth of February, 1663, towards half past five in the evening, a loud roaring was heard at the same time throughout the length and breadth of Canada. This noise ... made all rush outdoors ... people were much surprised to behold walls tottering, and all the stones in motion as if they had been detached. Roofs seemed to bend down in one direction, then back again in the other; bells rang of their own accord; beams, joists and boards cracked; and the earth leaped up, and made the palisade-stakes dance in a way that would have seemed incredible had we not witnessed it in different places *(Jesuit Relations, 1663)*.

Thus begins the documented history of earthquake occurrence in Canada. This account of an earthquake near Quebec City is taken from the annual report by the Society of Jesus to Rome, covering the period from the summer of 1662 to that of 1663. The first account of an earthquake on the west coast is to be found in the journal of Captain George Vancouver. There he noted that in 1793 a severe earthquake shock had been felt at the Spanish settlement of Nootka on the west coast of Vancouver Island (Vancouver, 1793; Rogers, 1992).

The history of earthquake engineering in Canada will be traced from these beginnings to 1997. The early years are dominated by a few personalities and it is easy to convey the sense of evolution. This period ends about 1953 when the first seismic design provisions were incorporated in the building code. From this point, the major impetus for development comes from national organizations such as the Geological Survey of Canada, the Canadian Council on Earthquake Engineering, engineering consultants and universities. In dealing with this period, the focus is on the organizations, not individuals. This strategy is deliberate to avoid the problems of trying to deal fairly with the significant contributions of individuals who are still active, in the limited space available.

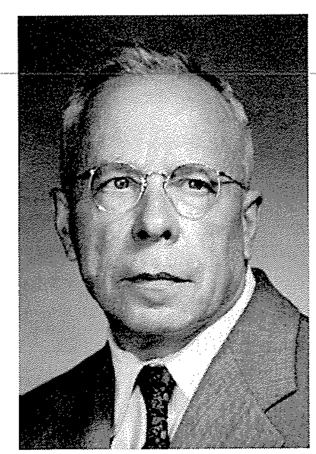


Fig. 1.E.A. Hodgson.

The Early Years to 1953

Scientific observation of earthquakes in Canada began when the British Association for the Advancement of Science established a world seismograph network that included stations at Toronto (1897) and Victoria (1898). These stations were operated by the federal Meteorological Services of Canada until they were turned over to the Dominion Observatory in 1936 (Stevens, 1980). The first Canadian seismogram was recorded in 1897 on an instrument at McGill University that did not operate continuously (Basham and Newitt, 1993).

F.N. Dennison was the first seismologist at Victoria Observatory. He became Director in 1914 and operated the seismographs until his retirement in 1936 (Rogers, 1992). The first seismologist appointed to the Dominion Observatory in Ottawa was O.J. Klotz.

With the assistance of E.A. Hodgson he produced lists of Canadian earthquakes which were published in annual reports. During his regime the seismic network expanded across Canada.

E.A. Hodgson became head of the Seismological Division of the Observatory in 1924 (fig. 1). It was a fortunate event. He gained international recognition for Canadian seismology and successfully bridged the gap between seismology and earthquake engineering. He is noted for the extensive damage assessments he conducted after major earthquakes. His papers, and comprehensive report on the 1924 M=6.5 La Malbaie earthquake in Quebec, constitute the first detailed scientific study of a Canadian earthquake. However, because of Quebec's concern about the negative impact that the report might have on investment and development, this study was not published until 1950 (Hodgson, 1950).

In 1945, Hodgson presented the distilled wisdom of his field studies to the Montreal section of the American Society of Electrical Engineers (Hodgson, 1945). This paper is a glorious example of technology transfer. It is written in an engaging witty style rarely seen in technical writing today. On the on-again off-again interest of the Canadian public in earthquake hazards and mitigation he had this to say: "the curve of Canadian public interest in earthquakes resembles the chart of a patient with undulant fever." In response to that perennial question, "When will the next major earthquake likely take place?"-he quoted Mark Twain, "I was gratified to be able to answer promptly and I did. I said I did not know."

Hodgson's observations on earthquake hazards in this paper have retained substantially their validity even after 50 years. The more important examples are:

In no Canadian earthquake has there been any authenticated evidence of rock faulting. [There is now one exception, the 1989 Ungava, Quebec earthquake, M=6.3].

... alternate layers of silt and sand. This type of ground when wet flows like a liquid.

What single factor is the most important in determining the distribution of destructiveness in the epicentral region? By all means the nature of the terrain.

... damage is very much greater on deep alluvium, on made ground, on fairly deep soil on a sloping base of rock or clay or in places where there is relief on one side of the point in question as in the case of a river, lake or ravine.

Hodgson had a cooperative attitude towards those connected with mitigating the effects of earthquakes, such as earthquake engineers, public utilities and municipal governments. This attitude is still a distinguishing characteristic of the Geological Survey of Canada seismologists in Ottawa and at the Pacific Geoscience Centre in Sidney, BC.

Hodgson was a member of the Board of the Seismological Society of America (SSA) from 1926 to 1952, and served two terms as president, 1941-1942 and 1942-1943. In all his 26 years on the Board, he never attended a meeting of the association! He was succeeded on the Board by his son John in 1952 (J.H. Hodgson, 1989).

Developments from 1953 to 1957

The National Building Code of Canada (NBCC)

A large part of the practice of earthquake engineering in Canada is devoted to the implementation of the seismic provisions of the NBCC in structural design. The first edition of the NBCC was published in 1941. The scanty seismic provisions were relegated to the Appendix. The seismic provisions were updated and placed in the main text in the 1953 edition. The provisions were referenced to a seismic zoning map prepared by J.H. Hodgson (1956), who had succeeded his father as Head of the Seismology Division in 1952. This map divided Canada into 4 seismic zones based on estimated damage potential

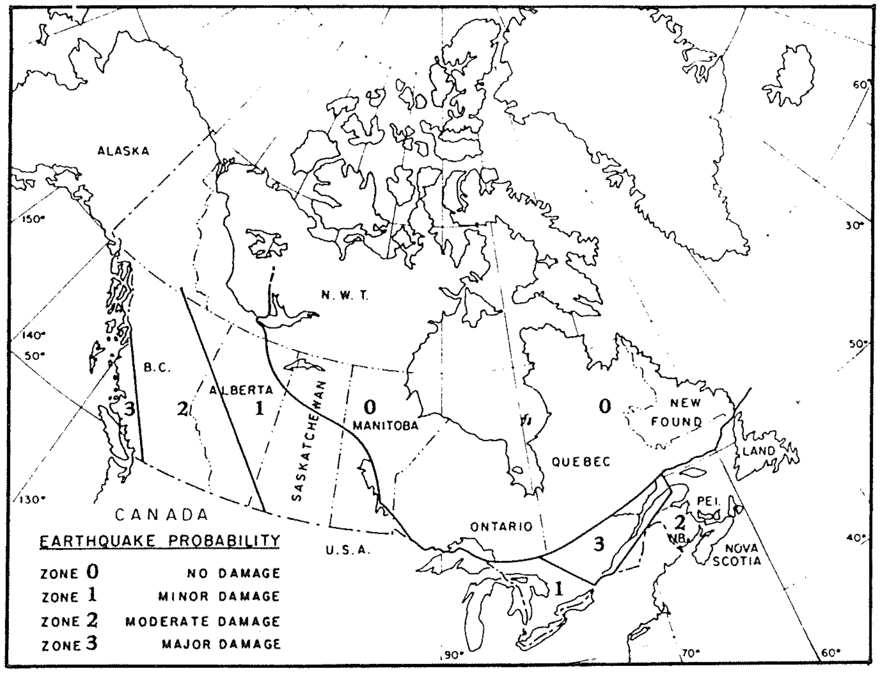


Fig. 2. First seismic zoning map of Canada.

from future earthquakes; zone 0 = no damage, zone 1 = minor damage, zone 2 = moderate damage and zone 3 = major damage (Fig. 2). The coast of British Columbia and the St. Lawrence valley, both in zone 3, were considered to be seismically comparable to California (Basham and Newitt, 1993).

The first probabilistic hazard map (one of the first in any country) appeared in the 1970 NBCC (Whitham et al., 1970). It was based on statistical studies of Canadian seismicity by W.G. Milne of the Victoria Observatory and included earthquakes from 1900 to 1963. Milne and Davenport (1969) applied Gumbel's extreme value method to these data to establish peak ground accelerations with a probability of exceedence of 0.01. These accelerations were used to establish bounds for 4 seismic zones similar to those produced by Hodgson (1956). Milne was later appointed chief scientist of Pacific Geoscience Centre in Sidney, B.C. when it opened in 1980 (fig. 3).

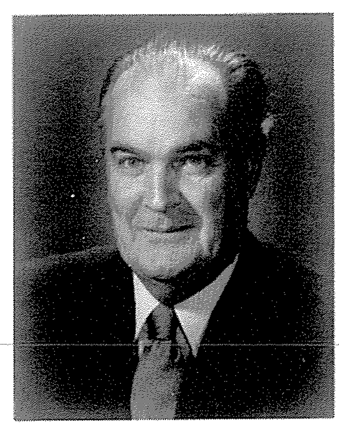
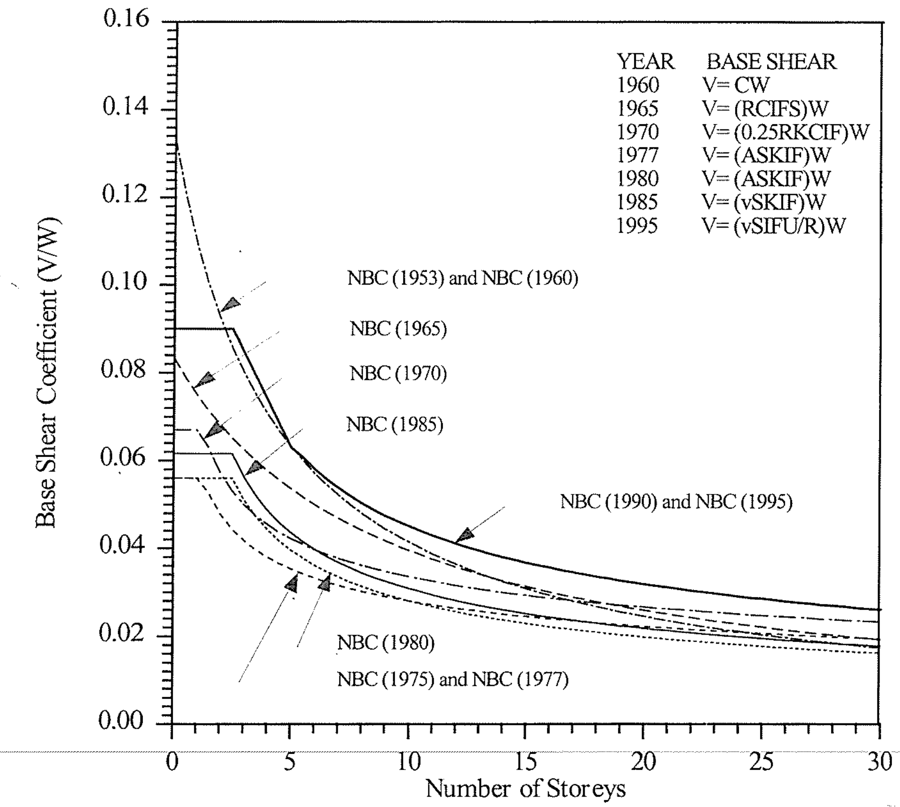


Fig. 3. Dr. W.G. Milne.

The next major change in seismic zoning occurred in 1985. Two seismic hazard maps were produced, one for accelerations and one for velocities, to better represent the effects of different frequencies on structural response. The maps were based on the earthquake catalogue up to 1982, and revised ground motion attenuation relations for accelerations and velocities. At this time, the federal seismologists were incorporated into the Geological Survey of Canada.

New trial seismic hazard maps have been published for NBCC 2000 (Adams et al., 1996). The new maps reflect earthquake occurrence to 1993. The seismic design provisions in this draft code reflect a new basis for seismic design, using a uniform hazard response spectrum, ensuring an equal probability of hazard for each period of structural response. Also, for the first time, the effects of the Canadian subduction earthquake have been taken into account. This has been done in a deterministic fashion. Whenever the predicted ground motion from the subduction event exceeds the probabilistic values from the crustal source zones, the subduction motions have been used to define the hazard. Because of the estimated distance of the potential subduction source from Victoria and Vancouver, seismic design in these cities is not controlled by the subduction earthquake.

Over the years, the procedures for determining the seismic design loads on buildings has also evolved from the primitive procedures of the 1950s. The basis of seismic design is the design-based shear for buildings. This depends on the intensity of shaking, the period of the building, the structural form, and the materials of construction. Each of these factors is represented by a parameter in the formula for calculating base shear due to earthquake excitation. These parameters have evolved on the basis of research findings and the performance of different types of buildings in earthquakes. This evolution may be traced in the changes in design base shear on firm ground from 1953 to 1995 as shown in fig. 4. This is an update of an earlier plot by Uzumeri et al (1978). A notable difference between the present code and previous codes is the much higher seismic demand attributed to long-period buildings. In the short-period range, the demand had been dropping since 1953 but increased again in the present code. These later changes reflect primarily a greater understanding of the seismic hazard.



Variation of NBC Base Shear Coefficient, V/W (Update of plot by Uzumeri et al., 1978)

Fig. 4.Evolution in design base shear requirements for firm ground conditions from 1953-1995.

Canadian Council on Earthquake Engineering (CANCEE)

CANCEE was founded in 1964 to advise the Natural Research Council (NRC) on the seismic provisions of the building code, to represent Canada to the International Association for Earthquake Engineering (IAEE) and to promote seismic research and practice in Canada. Sheldon Cherry of the University of British Columbia was the founding chairman. He was succeeded in 1975 by Art Heidebrecht of McMaster University who was followed by Mike Uzumeri of Toronto University in 1981. The current chairman, Ron DeVall of Read, Jones, Christoffersen in Vancouver, took office in 1988.

In 1990, NRC reorganized its committee structure. A new CANCEE emerged, restricted in its terms of reference to providing advice on the seismic provisions of the NBCC. This left Canada with no organization to represent it nationally and internationally in earthquake engineering affairs. Concern about this issue, and about the future of the triennial national conference on earthquake engineering, which used to be sponsored by CANCEE, led to the formation of CAEE/ACGP, the Canadian Association for Earthquake Engineering/L'association Canadienne du Geniè Paraseismique.

The CAEE/ACGP was incorporated in 1993, with the objective of promoting earthquake engineering research and practice in Canada and sponsoring the National Earthquake Conference. Shel Cherry was the founding president and a core group of founding directors were selected from CANCEE (Peter Basham of GSC, Cherry, DeVall, Finn, Heidebrecht and Uzumeri). The current president, Art Heidebrecht, represented Canada at the 11th World Conference on Earthquake Engineering in Mexico in 1996. At the same conference Shel Cherry was elected as the first Canadian president of the International Association for Earthquake Engineering.

Geological Survey of Canada (GSC)

The GSC is responsible, among other things, for monitoring and studying Canadian earthquakes and assessing seismic hazard. It operates a network of 100 digital seismographs throughout the country, and locates and catalogues about 1,500 earthquakes a year. It also maintains strong motion seismograph networks on the West Coast and in the St. Lawrence Valley. Strong motions have been recorded to date from 5 Canadian earthquakes including the 1986 Nahanni earthquake, which had the highest ground acceleration ever recorded, in excess of 2 g.

In the early 1970s, the GSC got involved in reviewing the seismic design criteria being developed by Ontario Hydro for its nuclear power plants. Since there were no existing standards, the Canadian Standards Association (CSA) set up CSA committee N289 on "Seismic Qualification of Canada Nuclear Power Plants." The GSC played a major role in the development of this standard. The N289 standard ensured that a standard for Canada reactors was available, which could be used around the world.

It is interesting to note that independent judgment was brought to bear later on these early contributions of GSC seismologists. In the case of Energy Probe versus the Attorney General of Canada in 1993, a report on the safety of Canadian nuclear plants by Weston Geophysical Corporation, Wesboro, Massachusetts, was filed as an exhibit. The report stated that the seismologists of the GSC "have acquired an outstanding reputation on a national and international scale for the high quality of their studies."

In addition to their work for the NBCC, the GSC is also assisting CSA in the formulation of seismic design standards for critical facilities, reviews environmental impact statements for industrial projects and advises the insurance industry on risk potential.

GSC scientists are working on a number of seismic projects on the West Coast, including developing the geological architecture of the Fraser Delta, and conducting fundamental research on the major seismic threat posed by the subducting Juan de Fuca plate. The potential subduction earthquake, often called the "Big One," is expected to have a magnitude in the range of 8 to 9.

The Fraser Delta, which is an area of major development and population increase, is very susceptible to liquefaction during earthquake shaking. To provide a proper basis for evaluating the seismic hazard in this area, GSC scientists are drilling a limited number of holes to bedrock, or to the Pleistocene deposits underlying the deltaic deposits. They have also conducted many cone penetration tests and shear wave velocity studies, to define the stratigraphy of the delta and the properties of the liquefiable sediments. Studies like these are essential for a proper understanding of ground motions, such as those recorded at 7 sites in the delta during the 1976 Pender Island, B.C., and the 1996 Duvall, Washington state earthquakes. The Duvall records, which are the first digitally recorded strong motions in the delta, are expected to contribute substantially to our understanding of ground motion amplification by the relatively loose deltaic sediments.

A very interesting feature of the liquefaction investigations are the studies of paleo-liquefaction, being conducted by the GSC in cooperation with local geotechnical consultants. Today about 6 sites have been identified in the delta. None of these sites suggest that liquefaction occurred less than about 1,500 years ago. Considering the relatively low levels of base motion required to cause liquefaction in the delta, this evidence tends to suggest that the Lower Mainland of B.C. has not been subjected to very strong shaking in that time, despite the fact that the last large subduction earthquake occurred about 300 years ago. This evidence tends to confirm the findings from the seismic studies conducted for the National Building Code by the GSC, that the subduction earthquake occurs too far from Vancouver to be a major threat to the Lower Mainland.

The energy and shaking of the potential subduction earthquake is so large that it is imperative that fundamental research on the interaction of the Juan de Fuca plate and the North American plate continue to be conducted. Scientists at the Pacific Geoscience Centre have produced very useful tentative models of the subduction zone. However it is becoming increasingly difficult to maintain the volume and quality of the research, as research funding decreases and staff levels shrink. In view of the seismic threat to the rapidly growing west-coast population centres, and Canada's limited ability to respond to major earthquake disasters, a review of Government policy on seismology and earthquake engineering research is imperative.

Consultants

As earthquake engineering research developed in Canada, and the universities began to produce qualified graduates in structural and geotechnical earthquake engineering, Canadian consultants and large organizations, such as BC Hydro, Ontario Hydro, and Quebec Hydro, developed in-house capability to deal with earthquake hazards. Their work on critical facilities, such as nuclear power plants, large dams, major bridges, essential post-disaster structures, LNG tanks, and major pipelines, pushed the level of Canadian practice in earthquake engineering to the highest international standards. A recent result of their efforts is that Canada is the first country to have issued nationally accepted safety guidelines for dams.

The Role of Universities in Research

More than half of the Canadian population is exposed to a significant seismic hazard. Both the eastern and western regions of Canada have active seismic zones and face the risk of major losses due to earthquakes. This potential seismic risk has motivated Canadian engineers and scientists to engage in earthquake engineering research. Their research activity has resulted in significant contributions to knowledge in this field. However damage patterns from major recent earthquakes, such as Loma Prieta (1989), Northridge (1994) and Kobe (1995), show that there is a continuing need for sustained research in earthquake engineering, especially the testing of large-scale models in the laboratory and full-scale structures in the field. The Saguenay earthquake in Quebec in 1988 was especially valuable in providing data on the special characteristics of eastern earthquakes, which are felt over much wider regions than similar-sized earthquakes in the west.

Earthquake engineering research capability in Canadian universities has changed dramatically in the last five years. Laboratory facilities have been created, which can test large models in dynamic, slow cyclic and large displacement modes. In discussing the role of the universities, the report concentrates mainly on these new developments.

University of British Columbia

The first formal program in earthquake engineering was established at the University of British Columbia (UBC) in the mid-1960s, motivated by the damage caused by liquefaction during the 1964 earthquakes in Alaska and Niigata. Similar damage was considered likely in the Fraser Delta in British Columbia. With support from the National Research Council (NRC), a medium-sized shake table was installed at UBC, with a nominal 22 kN (5,000 lb.) capacity horizontal actuator, and cyclic triaxial and simple shear equipment for the dynamic testing of soils were developed. A graduate research program in geotechnical earthquake engineering was initiated with some of the first courses on soil dynamics in the world. The program quickly extended to structural engineering and the first Canadian conference on earthquake engineering was held at UBC in 1970.

The geotechnical group has made significant contributions to earthquake engineering over the last 30 years. Fundamental laboratory investigations contributed to understanding of the mechanism of liquefaction and post-liquefaction behaviour. Some of the first controlled liquefaction experiments on shake tables were conducted at UBC, in which the distribution of accelerations and porewater pressures were measured. A unique feature of the test program was the ability to apply various levels of overburden pressure to the shake table models, using air pressure acting on a surface membrane. The group pioneered nonlinear dynamic effective stress analysis and the analysis of post-liquefaction flow deformations. Major contributions have been made in the development and interpretation of in-situ tests especially the use of the cone for assessing liquefaction potential, the seismic cone for measuring shear wave velocity and damping, and the pressuremeter to assess fundamental in-situ stress-strain response for use in liquefaction assessment. Research on the Becker Hammer Test, for assessing liquefaction of gravels, has resulted in procedures for measuring the delivered energy to the Becker casing and correcting the blow counts to the standard energy level. Procedures were also developed for including the effects of friction on the casing during driving.

The first large shake table capacity in Canada was installed at UBC about 20 years ago. The shake table is a 3 m x 3 m aluminum cellular structure with a payload capacity of 156 kN (35,000 lb.). For about twenty years, the table was operated as a single-axis earthquake simulator and was used extensively for research, as well as for qualification tests of equipment and structural components. The original design included provisions for future conversion to a multi-axis shake table. In 1996, the table was upgraded by adding four hydraulic actuators, and signal controller and amplifiers. Digital control software tracks simultaneously the displacement, velocity and acceleration of each actuator during off-line compensation calculations. The four new actuators can generate up to 67 kN (15,000 lb.) each. All the actuators in the system have a maximum displacement of 7.6 cm. The shake table can now be operated in one of two configurations. The first configuration can be used to simulate one horizontal, the vertical, and the pitch and roll motions, while the second configuration can be used to simulate two orthogonal horizontal motions and yaw motions.

The cost of this upgrade was about $550,000. Funding for the upgrade was provided mainly by BC Hydro, the Natural Science and Engineering Research Council of Canada (NSERC), the BC Science Council, and the Department of Civil Engineering at the University of British Columbia.

Quebec

McGill University and École Polytechnique in Montreal, and the University of Sherbrooke, have developed a strategic research program in earthquake engineering. Combined financial support from the Natural Science and Engineering Research Council (NSERC), and the Institutions themselves for this research program, approaches the $3 million mark. The major equipment at each university is complementary: McGill concentrating on cyclic loading, École Polytechnique on shake table studies, and Sherbrooke on large displacement studies.

The horizontal uniaxial shake table at École Polytechnique has plan dimensions of 3.43.4 m with a specimen payload capacity of 15 tons. The shake table itself weighs 6.9 tons and is fabricated from an all-welded multicell steel construction. The shake table is mounted on four hydrostatic linear bearings. The shake table is driven by a 250 kN fatigue-rated hydraulic actuator activated by a 730 l/min (190 gpm) hydraulic power supply. The usable peak-to-peak stroke of the shake table is 250 mm, and a maximum horizontal acceleration of 1.0 g can be achieved for a fully loaded table. A key feature of the table is a digital control system, which allows accurate simulation of specified earthquake ground motions.

In the area of structures, the research activities of these institutions are also complementary, with McGill specializing in concrete and steel structures, École Polytechnique in steel structures and the seismic response of earth structures, and the University of Sherbrooke playing a leading role in research on residual strength of liquefied soils and in the retrieval of large undisturbed samples.

Ottawa-Carleton Earthquake Engineering Centre

The Ottawa-Carleton Centre has been established as a joint research centre of the University of Ottawa and Carleton University. Its objective is to foster research in earthquake engineering at the two universities as well as to bring together researchers from industry, government agencies, and universities in the National Capital Region, who are active in the field of earthquake engineering.

The Centre has a full scale multi-degree-of-freedom pseudo-dynamic testing facility (the only one in Canada, and one of the few world-wide), located at the University of Ottawa.

The major upgrading in the experimental research facilities of Canadian universities, described above, places Canada at the forefront of experimental earthquake engineering research.

University of Alberta

One of the major developments in geotechnical earthquake engineering in the 1990s is the Canadian Liquefaction Experiment (CANLEX). This is a national cooperative research effort between universities and industry, to improve capability for evaluating liquefaction potential, and modelling pre- and post-liquefaction behaviour.

CANLEX was the initiative of the soils group at the University of Alberta, who are the chief investigators and manage the project. Results to date from the experiment indicate that CANLEX will be one of the landmark events in geotechnical earthquake engineering. Already standards have been set for obtaining and testing frozen samples from the ground, and improving and extending the interpretation of cone penetration data for assessing liquefaction potential. Furthermore the role of the cone as an investigative tool has been expanded by extensive correlations with laboratory and field data. Also, a new framework for characterizing soil behaviour, including liquefaction, has been developed, which provides a framework for understanding the complicated mechanics of the liquefaction problem.

University of Toronto

Engineers at the University of Toronto have played the leading role in establishing the seismic requirements for concrete structures.

McMaster Earthquake Engineering Research Group

The McMaster group have operated a small shake table facility (one degree of freedom) since 1969, and have a variety of other dynamic and static testing facilities in the Applied Dynamics Laboratory. They developed a strong-motion database, which was used quite extensively from about 1985 to the early 1990s. However limited research funds prevented them from adding new records since then.

Typical Research Projects

Shake Table Tests

Some typical examples of how universities can contribute to Canadian industry and the engineering profession, in the area of earthquake engineering, are provided by projects completed on the upgraded UBC shake table. These include testing of 18 plywood shear wall specimens representative of those used by a Canadian company for home construction in Japan, testing of office furniture for one of the major vendors in Canada, and testing of connections of heavy timber frames (see fig. 5). Tests to failure were conducted on scaled models of the Oak Street Bridge in Vancouver as part of a retrofit study. Tests on concrete gravity dam models, to assess the effects of friction at the dam/foundation interface on seismic response, were conducted in collaboration with BC Hydro as part of their dam upgrading program.

Vibration Measurements on Large Civil Engineering Structures

Researchers at École Polytechnique in Montreal, University of Sherbrooke, McMaster University and the University of British Columbia, have been active in vibration measurement studies of large civil engineering structures, to gain a better understanding of their dynamic properties and characteristics. Another important purpose of such studies is to determine whether or not damage has occurred during an earthquake. This can be accomplished by placing permanent instrumentation on the structure, or by conducting vibration tests before and after the damaging event. A number of techniques for damage detection, based on such measurements, are available.

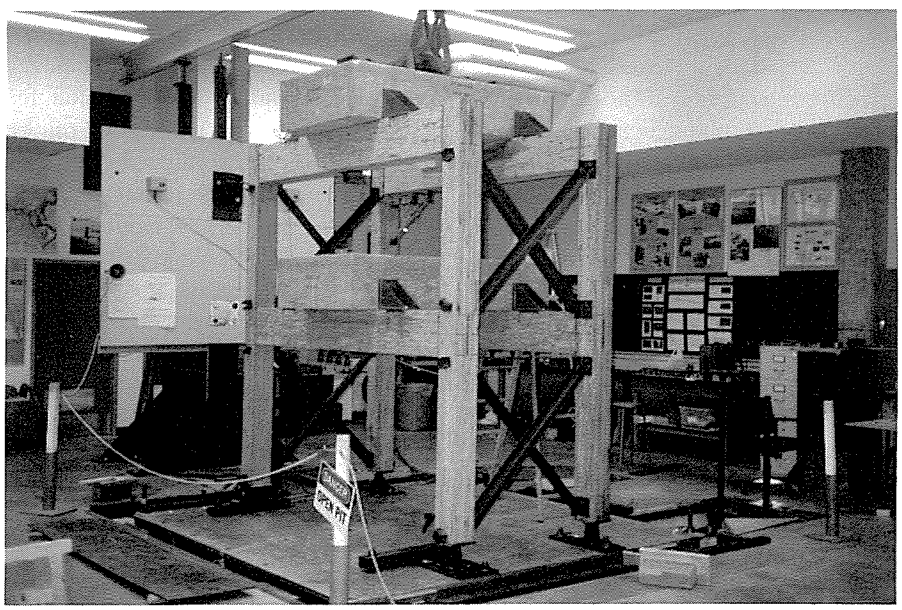


Fig. 5.Test on heavy timber frame.

Structural vibrations may be induced by artificial means or may be caused by natural phenomena. The techniques commonly used to induce forced vibrations include the use of shakers, impact loading, and quick release from an initially deformed position. Natural phenomenon that cause vibrations in a structure include low-level ambient vibrations, strong wind, and ground shaking. The key to obtaining useful vibration data and reliable results is the use of appropriate measurement equipment and signal processing software. In recent years, both the quality of instruments available and the capability of signal analysis hardware and software have improved tremendously. A few examples of this kind of research is given below.

Painter Street Overpass

As part of a research program funded by a joint strategic grant to the University of British Columbia (UBC), McGill University and the University of Ottawa, ambient vibration tests were conducted on the two-span Painter Street Overpass in the Cape Mendocino area in Northern California. This bridge has permanent instrumentation which has provided records of motions from more than ten significant earthquakes in the area, with peak accelerations on the deck reaching 1.0 g. The evolving behaviour of the bridge has been traced from ambient vibration levels up to the most severe level of shaking. These data are now being used to evaluate the response of the pile foundations of the bridge as part of a study under a second strategic grant to the same universities.

Queensborough and Port Mann Bridges

Ambient vibration tests were conducted on Queensborough and Port Mann bridges by UBC to help engineers calibrate their computer models so that they could properly replicate the mode shapes and frequencies of the bridges for their retrofit studies.

These two bridges were tested in collaboration with a vibration testing company established by a former student of UBC who did his research work on ambient vibration testing techniques as part of a professional partnership program with the BC Ministry of Transportation and Highways.

Ruskin Dam

This concrete gravity dam near Mission, east of Vancouver, is being seismically evaluated by BC Hydro. In partnership with BC Hydro, vibration tests were conducted on this dam by UBC to determine its dynamic characteristics. The objectives of the study were to determine whether or not individual blocks of the dam move independently and to evaluate the variation of the natural frequencies of the dam as a function of the elevation of water in the reservoir.

Thirty-Storey Building

Extensive vibration measurements were conducted on City Crest Tower a reinforced concrete building in Vancouver during different stages of construction (see photograph fig. 6).

These measurements were used to determine how the dynamic characteristics of the building changed with increasing height of construction, and to assess the effects of setbacks on the torsional response of the building. Setbacks pose difficult problems in seismic design.

Professional Partnerships: New Role for Universities

The concept of professional partnerships with consultants, major utilities and government agencies, was developed by the Department of Civil Engineering at the UBC. The basic idea is for employees of these organizations to come to UBC to do research on problems of major interest to employers. The employees are supported by their own organizations. The research work is supervised in the usual way by a professor, but it is also monitored by a committee which includes senior engineers of the supporting organization.

The program is a very effective way of transferring state-of-the-art technology to industry and ensuring that the departmental research program has a component of relevant applied research. Two examples of the kind of work being done under the professional partnership program are given below. The partners were BC Hydro and the BC Ministry of Transportation & Highways.

Fig. 6.City Crest Tower, Vancouver, B.C.

BC Hydro

This project involved the assessment of the structural capacity of timber pile supported transmission towers in the Fraser Delta to resist liquefaction-induced displacements. Laboratory and field tests were conducted to determine the response of the timber piles to large cyclic displacements. A method for analyzing the response of the laterally loaded foundations to cyclic loading was also developed.

BC Ministry of Transportation & Highways

This project involved the assessment of the seismic vulnerability of the George Massey Tunnel near Vancouver, on the freeway from Vancouver to Seattle. This tunnel cuts into the potentially liquefiable Fraser Delta sediments. In the study, a major challenge was to estimate the post-liquefaction deformations of the tunnel.

The Future

The most pressing demand on the earthquake engineering profession is to provide cost-effective retrofitting for existing structures subject to earthquake hazard.

This is the major rationale for the greatly expanded research facilities in Canadian universities, and for the many cooperative research ventures between universities and industry. The challenge now for the universities is to deliver the relevant research data on material performance, especially new materials and dynamic structural characteristics, and to provide the validated procedures of analysis that industry and society needs. These findings will also contribute to safer, better performing and more cost-effective new structures.

Recent earthquakes in California and Kobe, Japan, continue to show that great damage is associated with soil liquefaction. Measures to remediate liquefaction effects must continue to be a major focus of research for geotechnical earthquake engineers.

Acknowledgements

I wish to thank: Peter Byrne, Perry Adebar, Shel Cherry and Carlos Ventura of the University of British Columbia; John Cassidy, Gary Rogers and Dieter Weichert of GSC, Pacific Geoscience Centre, Sidney B.C.; Rene Tinawi of École Polytechnique, Montreal; Art Heidebrecht of McMaster University, Hamilton; Cyril Leonoff, Vancouver; and W.G. Milne, Victoria, for critical reviews of different drafts of this paper, helpful suggestions, useful information and incisive editorial suggestions. They made this a much better paper than it would have been without their help.

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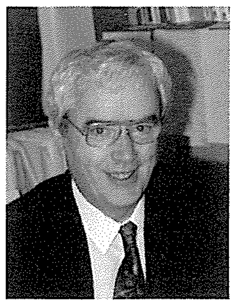

W.D. LIAM FINN is an engineering graduate of the National University of Ireland and received his master and Ph.D. degrees from the University of Washington in Seattle. He came to the University of British Columbia in 1961, was appointed head of civil engineering in 1964, and dean of applied science in 1969. He is currently professor of civil engineering. Dr. Finn is an honorary research professor of the Central Institute Building and Construction, Beijing, and an honourary member of the Chinese Society for Soil Dynamics.

Dr. Finn was a visiting professor at the University of California, Berkeley, in 1964, working with Professor Harry Seed, the father of geotechnical earthquake engineering, when the great earthquakes occurred in Alaska and Niigata, Japan. (Dr. Seed began a research program in soil dynamics to assist with decisions on reconstruction in Alaska.) When Dr. Finn returned to UBC, he started the Geotechnical Earthquake Engineering Program supported by the National Research Council of Canada. The program was later expanded to include structural engineering.

Finn has authored over 250 technical publications in the field of soil dynamics and earthquake engineering and has developed practical computer programs for dynamic analysis, probabilistic liquefaction assessment, and post-liquefaction deformations. Dr. Finn is an active consultant on the international level. He is an associate editor of the *International Journal of Soil Dynamics and Earthquake Engineering.* He is a director of the International Society for Numerical Methods in Geomechanics and a member of the Canadian Association for Earthquake Engineering. He is also a member of the Canadian Council on Earthquake Engineering, which is responsible for the seismic provisions of the National Building Code of Canada. Dr. Finn was the Canadian Geotechnical Society national lecturer in 1991.

The St. Lawrence Seaway

F. Lionel Peckover

"An enormous undertaking!" "The engineering marvel of our time!" "Creating a new North American seacoast!" Such was the hype surrounding construction of the St. Lawrence Seaway and Power Project in the 1950s. The enthusiasm among Canadian engineers was reflected in the reply of Professor I. F. Morrison of the University of Alberta when asked what to do if Seaway construction became a reality. "Only one thing," he said. "Get on it!"

Brief History

The start of the Seaway was the culmination of many decades of dreaming, planning and negotiation. Before 1700, a small canal to take freight canoes was built to bypass the Lachine Rapids at Montreal. By 1793, the Royal Engineers had built small canals only 21/2 ft deep to avoid the rapids at Lachine and Beauharnois (map in fig. 1). By 1904, canals to bypass all the rapids on the St. Lawrence River between Montreal and Lake Ontario had been built by the federal government to successive depths of 5, 9 and finally 14 ft.

Welland Canal (Courtesy of The St. Lawrence Seaway Authority).

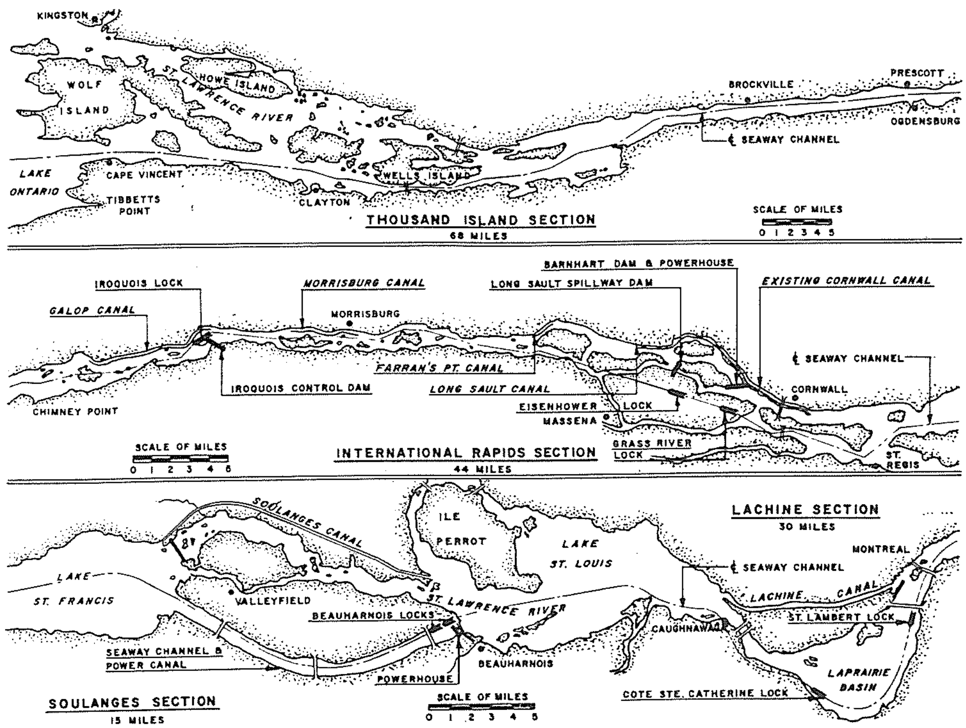

Fig. 1. General location plan of Seaway route.

The last of a series of canals between Lakes Ontario and Erie, the fourth Welland Canal was opened in 1932, with a channel depth of 25 ft. The new St. Lawrence Seaway was built to a navigable depth of 27 ft and the Welland Canal deepened to the same depth during Seaway construction. With remarkable foresight, the Beauharnois Power Canal had been opened in 1932 with provision for a future Seaway channel. As a result, on the opening of the Seaway in 1959, ocean ships of 27 ft draught could access all the Great Lakes, being lifted some 600 ft en route.

Before this, with the approval of the International Joint Commission, Ontario Hydro and the Power Authority of the State of New York had agreed in 1952 to develop power jointly on the river in the Cornwall/Massena area.

In 1951 the Canadian government had unanimously passed the St. Lawrence Seaway Act and formed the St. Lawrence Seaway Authority to build an all-Canadian Seaway. This was in the face of repeated refusals of the U.S. Congress, under intensive lobbying by railways, coal mining interests, and eastern seaboard ports and shipping interests, to participate in joint construction of the project.

When the author joined the Seaway project staff in late 1953, a priority task was to design two Canadian locks in the international section of the river just upstream from Cornwall. At this time the U.S. Congress decided that they did not want to be left out of the action and it was with some reluctance that we shelved our plans, as they joined in.

Evidence of our serious intent remains in a large structure in the dike near the Canadian side of the powerhouse. Now closed by stoplogs, it is designed to accommodate the upper gates of a lock if an all-Canadian Seaway is ever built. All locks on the project are built to allow for twinning if future traffic warrants.

Scope and Preparation

Even with the shared work, the Seaway project seemed vast and complex. Five of the seven locks were to be built in Canada, a channel provided along the river from Montreal to Lake Ontario, and the Welland Canal deepened. In the Canadian work alone 52 million cu yd of earth and 24 million cu yd of rock were moved and 2 million cu yd of concrete placed. All significant engineering and construction work was to be done in the daunting schedule of four years .

Excluding the Welland Canal, total cost of the Canadian Seaway work was two billion current dollars. Cost of soil engineering work on the project, in terms of the value of contracts directly involved, was:

- Subsurface exploration and tests
  0.25 per cent
- Design, assistance with preparation of contracts, construction consultation and control
  0.33 per cent
- Total
  0.58 per cent

The American portion of the Seaway at Massena was the responsibility of the St. Lawrence Seaway Development Corporation, with the U.S. Corps of Engineers as its construction agent. The St. Lawrence Seaway Authority was responsible for the Canadian work with its engineering headquarters in Montreal.

Interwoven with construction of the ship channel were the tasks of designing and building structures ranging in size from pump houses to navigation locks, moving of utilities, maintenance of services to industries, communities and even individuals along the way; accommodation of road and rail traffic across the channel (fig. 2) and at the same time maintenance of ship traffic through the existing canals. All this was to be coordinated with work on the American portion of the Seaway and that of the power authorities.

If it is realized that this was all before the development of critical path analysis, to say nothing of computers, the formidable tasks facing the Seaway engineering staff can be appreciated. The person appointed to meet these challenges was Lawrence Burpee, deputy chief engineer. He served under chief engineer A. G. Murphy who looked after more official duties.

Lawrence Burpee came from the well-known western Canadian firm of Northern Construction and J. W. Stewart Ltd. and brought with him two of his very competent engineers. One was a specialist in the efficient use of construction equipment, an expertise that was repeatedly applied on the job, to avoid unnecessary delays and keep the work on schedule.

Mr. Burpee was an exceptional engineer and leader. His staff was intensely loyal, knowing that he had full confidence in them. And, remarkably for those times, he had a full appreciation of the role of geotechnical engineering in the project. As a result, it can be said that the Seaway was the most important public project in Canada up to that time, in which geotechnical engineering played an essential part throughout.

Professor Jacques Hurtubise of École Polytechnique in Montreal was appointed soil and foundation engineering consultant to the project in early 1953. His experience included many major construction projects in Quebec. Having just left the NRC Division of Building Research, the author was fortunate to hear of the need for engineering staff on the Seaway and came on board in late 1953 to head up the soil engineering section, reporting to Mr. Burpee. Jacques Hurtubise served as a "wise head" to us both throughout the project.

The soils staff soon grew, although within a tighter budget than we wished. The eventual number was 22 engineers and technicians, all with applicable experience. At the end of the job they took their augmented skills to various parts of Canada. The names of George Tustin (assistant section head), Don Bernard, Al Dyregrov, George Luck, Bob Spence, Roy Tanner and Alan Thorley will be familiar to some readers.

We were keenly conscious of our small numbers, particularly when discussing mutual problems with Corps of Engineers' staff. On these occasions we usually tried to get Ontario Hydro involved too, knowing that they could add extra "troops" to the man or two we could spare. The Americans must have wondered how we could manage our work with such thin representation. Sometimes we did too!

Technical Aspects

Our work encompassed almost the entire current scope of geotechnique to some degree. And yet, after four decades, the most lasting impressions are those relating to professional practice: the effective management of the work; excellent cooperation with Ontario Hydro engineers; the tight schedule allowing detailed studies only where results were essential to the safe, economical and prompt completion of the work; and the valuable lessons in geotechnical practice.

Fig. 2. Starting construction of lower Beauharnois lock. Railway trestle in background to be diverted, then bridged across lock gate.

Soil Conditions and Contract Difficulties

Dense glacial till was predominant almost everywhere in the upper St. Lawrence Valley. It typically had almost equal proportions of silt, sand and coarse material with some boulders. With proper handling and compaction it was excellent for construction of dikes; excavation faces stood up well at steep slopes. At the Beauharnois locks, however, marine (Leda) clay occurred and had to be handled with care. Bedrock included shale, limestone, dolomite and sandstone, with igneous intrusions in some areas. A detailed account of site geology and soil properties is found in Ref 3.

With over 75, per cent of the work area initially under water, test borings were particularly important for planning and design. By the fall of 1953, borings were already under way from barges in the river. Good standard practice was followed in sampling and penetration testing. Rock, within the anticipated depth of excavation,was cored to a depth of 10 ft. More than 1,700 test borings were made during the work.

All soil samples and rock cores were examined and classified by Jacques Hurtubise and tests done as necessary at École Polytechnique. This procedure was followed throughout the project and ensured uniformity of data. Complete drill logs, material descriptions and test results were provided as information in contract documents. This eliminated the possibility of claims due to information withheld from bidders. On large and important contracts, an outline of local geology as it affected the work was also included.

There were few claims due to unexpected conditions. An important exception was at the Iroquois lock where an excavation up to 90 ft deep was required, involving 4.5 million cu yd of glacial till and 5,000 cu yd of bedrock. Two separate tills were encountered here and the lower one was unbelievably dense. Standard penetration test values averaged 120 blows per ft and ranged up to 600 blows. Natural unit weight sometimes exceeded 160 lbs per cu ft! Representative samples were displayed to bidders, the material was described as "very dense till" and special mention alas made of the blow counts.

The successful contractor used large shovels for excavation and made good progress at first. What we did **not** anticipate was that the till on exposed faces soon dried out and became cemented and, as a result and to our consternation, required drilling and light blasting to reopen a face. At the end of the contract, the contractor, in al1 seriousness, filed a claim for payment of all earth excavation at the same rate he had bid for excavating the 5,000 cu yd of rock. He did not succeed entirely but, with the aid of an "expert" witness, won a substantial increase in payment for excavating the till.

A contractor excavating for the control dam on the American side of the same Iroquois site ran into a different type of problem. In the contract documents, drawn up by the U.S. Corps of Engineers, the presence of boulders was noted but nowhere was the term "glacial till" used. The low bidder, whose experience must have been in non-glaciated regions, got the job with a price of 40¢ per cu yd. He showed up with a spanking new fleet of heavy earthmovers which he knew could easily handle any deposits of sand, silt or clay (components of the till) encountered. Results were predictably tragic. His machines made little progress loading the dense till, continually hanging up on boulders and running up exorbitantly high maintenance costs. He gave up after getting far behind schedule. The job was relet at more than twice the original unit price.

Low bidding created problems on several contracts. Many contractors were so anxious to have their names connected with the well-known project that they shaved their bid figures to dangerously low levels. As a result, our soil inspectors were kept busy ensuring that work was done to the required standards. Field testing labs were within reach of all such contracts.

On one project, where we had to stop work repeatedly for non-compliance with the specs, the job superintendent would pull out a camera, take a picture and stalk away, saying "see you in court." He never did, perhaps because we quickly started keeping our own file of photos of such situations.

It is perhaps inevitable that the pace of work on a large project leads to some short cuts or lack of communication. A notable and costly instance of this occurred late in the construction phase when final cleanup of the channel excavation was being done downstream of Cote Ste. Catherine lock. It was decided to add a ship turning basin on the lanyard side of the channel, involving excavation to channel depth over an area of about 1,500 by 2,000 ft. A competent design engineer looked up the logs of test borings along the adjacent channel, found no bedrock within excavation depth, and prepared contract documents accordingly. When excavation started, bedrock was encountered, rising throughout the basin area toward the river bank. And the worst was yet to come. Bedrock was normally a shale, which could easily be ripped and excavated. However, over nearly the whole area of the turning basin, surface shale was underlain by a 5 ft sill of igneous rock. Excavation was to extend to mid-depth of this intruded layer. The result was that drilling and light blasting had to be done at intervals of a few feet and quantities were much greater than expected. Such was the urgency of the work that at one time the author counted 97 pieces of equipment working in the area.

This exceptional instance of oversight would have been avoided with input from our previous experience and a couple of quick borings, but no-one thought to ask and every day counted.

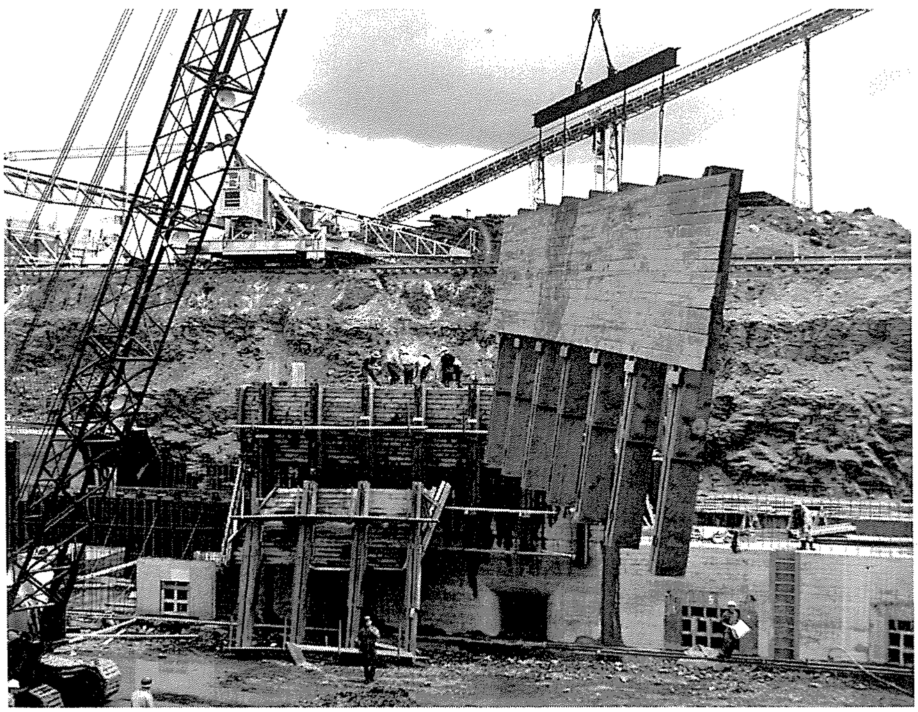

Fig. 3 Under construction (Courtesy of The St. Lawrence Seaway Authority).

Winter Construction of Fills

Many miles of dikes up to 30 ft high, were required on the project, mainly to maintain the water level in the navigation channel under fluctuating river levels. These fills, with a core of impervious till and shoulders of broken rock, were built according to current standards. To meet the construction schedule, however, some secondary earth fills had to be built in winter. As the natural water content of glacial till was close to the optimum for compaction, with proper attention the till was found satisfactory for winter placement. This was done in all but the most extreme weather by working rapidly in small areas with heavy equipment. Loaded trucks were used for compaction of the soil layers to leave the minimum surface area exposed to air.

Early in the program it was found that standard field-density testing was difficult and time-consuming due to the number of stones in the till material. Reliable nuclear density test equipment was not then available. This difficulty was particularly serious in winter placement of fills. A solution was found in the use of an oil immersion apparatus (originated by Fred Patterson of H.G. Acres and Co. and refined by Ontario Hydro), models of which were built for the job. Representative chunks of soil, dug with a pick, were trimmed, weighed and immersed in a graduated cylinder filled with oil to measure their volume by displacement. The method was naturally limited to soils with low permeability and some cohesion, but gave satisfactory results with some elementary precautions.

Cut Slopes on the Welland Canal

Ongoing with construction work on the St. Lawrence River, was the deepening of the Welland Canal between Lakes Ontario and Erie. Since its opening in 1932 it had operated with a channel depth of 25 ft., although lock sills provided a depth of 30 ft. for future use. Excavation to a channel depth of 27 ft was to be done in the dry below the Niagara Escarpment and by dredging above the Escarpment where the canal could not be drained. Both above and below the Escarpment, the canal was dug in stiff clay with side slopes of 2:1. Protection against wave erosion was provided.

Our initial inspection of the canal showed occasional slope failures, which had been treated by flattening of the slope or by unloading the top of the bank. Imagine our surprise, on looking through canal maintenance records to find that more than 250 slope failures had taken place during 25 years of operation! Apparently no comprehensive study of this continuing problem had ever been made. Slides had even occurred during construction; an official photo of the first ship passing through the canal with flags flying shows some bank slides in the background.

Much as we would have wished, we simply did not have the time to study this remarkable case history in depth. The records remain on file for analysis. We did note that slides occurred more frequently on the west side of the channel, probably due to the flow of ground water from that direction. An area of softer soil between locks 2 and 3 had more frequent slides and the toe of the bank had been cut back to improve stability.

Fig. 4 Aerial view upstream from Côte Ste-Catherine with Lachine Rapids in the distance. Lock construction is starting within the cofferdam. Channel excavation extends in the distance.

This previous experience enabled us to plan stable slopes for a 27 ft channel by back-analysis with selective soil testing. Slopes were either flattened to 21/2:1 or the top of the slope unloaded.

First Field Vane Used in Canada?

About 1957 I visited the Welland Canal which was being deepened from 25 to 27 ft. draught to match the depth of the new St. Lawrence Seaway. In talking with Mr. E.C. Shurly, Engineer of Construction for the Seaway, the conversation turned to ways of determining the strength of the local clay. To my astonishment, he said that during construction of the Welland Canal (1914-32), he himself had used a torsion vane to get some idea of clay strength. In fact he thought he knew where the vane might be stored.

He drove to a nearby building and soon came out with the vane. It was of welded steel construction, about 3 in diameter and 12 inches long with six blades, each about 1/8 inch thick. Mr. Shurly said that it was pushed or hammered down, then twisted using two spring balances attached to a T-handle. Comparative torques were recorded at various locations and depths.

As this instrument must have been used in the late 1920s at the latest, it may hve been the first field soil vane used in Canada. Elsewhere, it is known that John Olsson used a "vane borer" in Sweden as early as 1919.

For some reason, which I cannot recall, I did not ask to take the vane with me at the time, and on my next visit to the Canal it could not be found. Perhaps it is still gathering dust there. It would have made a interesting contribution to a geotechnical museum.

Some Memorable Experiences

On the American section of the Seaway work, substantial dragline excavation was necessary, to divert the river in order to build the power house and parts of the navigation channel. A Kentucky company, engaged in strip mining, won a contract and their 15 cu yd dragline, respectfully called "The Old Gentleman," complete with its Kentucky crew, set off for the Seaway. From the Mississippi River by barge into Lake Michigan, progress was slow as the machine often had to "walk" around small locks and other obstacles. But it finally arrived at the biggest hazard the Long Sault Rapids on the St. Lawrence.

A tug was hired and two cables connected to the barge. By pulling upstream, the tug was to guide the barge slowly down through the fast water. The dragline crew remained on board and, with the intuition of hard experience, had their bucket and gear in operating position with the moter running.

In the middle of the rapids one of the tug's cables broke and the captain, in panic, cut the other one. On their own now, the dragline crew cast their giant bucket overboard and used it as a stabilizing drag weight. Reaching a calm part of the river below the rapids, and taking out their maps, they realized that they were only a short distance from their work site. It was a simple matter to cast and winch their bucket a few times to reach shore. When puzzled authorities finally caught up with them, they were patiently waiting to start work.

The Seaway opening in June 1959 was a great celebration. The Americans had come to adopt the Seaway as their own and made detailed opening preparations. Hon. Lionel Chevrier, president of the St. Lawrence Seaway Authority, made some preparations of his own.

And so, as he tells it, when his U.S. counterpart proudly announced that President Eisenhower would cut the ribbon on their behalf and asked who would represent Canada, Chevrier was able to reply "Why, Queen Elizabeth, of course!" And that was how the opening ceremony came to be held at St. Lambert opposite Montreal, and the royal yacht "Britannia" became the first ship to officially proceed through the Seaway.

Summary

The total cost of geotechnical work was a little more than 0.5 per cent of the cost of related work, surely inexpensive for such an essential component of a project of this size and complexity.

For his leadership and perception, Lawrence Burpee well deserves a place on our honour roll of Canadian practitioners of geotechnique. And Professor Morrison had it right. None of us, who were connected with the project, failed to recognize that we had gained a sense of engineering teamwork and a store of geotechnical and professional practice to call upon during the rest of our careers.

Canadian geotechnical engineers can take pride in having a part in the completion of the largest joint Canadian-American heavy construction project in our history.

Acknowledgements

The author wishes to thank Roy Tanner, P. Eng., formerly on Seaway soil engineering staff, and Professor Robert Mitchell, P. Eng., of Queen's University, for reviewing the text and making many useful suggestions.

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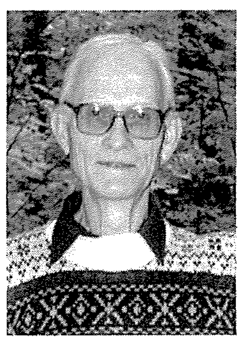

F. LIONEL PECKOVER obtained his civil engineering degree from the University of Toronto in 1944, where he was taught by Robert Legget, and studied soil mechanics at Harvard University under Karl Terzaghi and Arthur Casagrande.

On its founding in 1945, Peck was the first secretary of the National Research Council of Canada, Associate Committee on Soil and Snow Mechanics, and from 1947-53 first head of the Soil Mechanics Section, Division of Building Research, NRC, Ottawa.

From 1953-59 Peck was head of the Soil Engineering Section of the St. Lawrence Seaway Authority, Montreal, in charge of all aspects of the geotechnical exploratioin, design, and construction of the seaway project. Subsequently he was engineer of geotechnical services, Canadian National Railways, Montreal, being the first engineer employed in this capacity by a North American railway. Peck completed his career as a geotechnical consultant, which included terrain appraisal for high-speed rail lines in the Montreal-Windsor corridor.

Mr. Peckover is the author of over 40 technical papers and discussions, he has contributed to several book and manuals, and was co-recipient (with Dr. Doug Piteau) of the E.B. Burwell Jr. Memorial Award, 1982, from the Geological Society of America, for the best paper in the field of engineering geology.

The La Grande Hydroelectric Development - James Bay,Québec

Jean-Jacques Paré and Jerry Levay

Historical Context

The water, running from the interior of Québec to the west into James Bay and to the north into Ungava Bay, has been in demand since the early 1950s. At that time, it was thought that the headwaters of the La Grande and Caniapiscau basins were part of the Manicouagan-Outardes watersheds. Better topography later eliminated these areas from the Manicouagan-Outardes watershed and feasibility studies showed that it was uneconomical to divert water from there into the future Manicouagan Reservoir, which was created in the late 60s.

When a large block of energy was required in the early 70s, the water of the James Bay region again became of interest for the development of hydroelectric energy.

Although Hydro-Québec had been studying the potential of the Nottaway-Broadback-Rupert Rivers for several years, it was decided to develop the La Grande River first because, although the river was further away from the energy market, it was technically and economically more attractive (fig. 1).

Thus in 1971, the La Grande Project was begun under a cloud of political and environmental controversy.

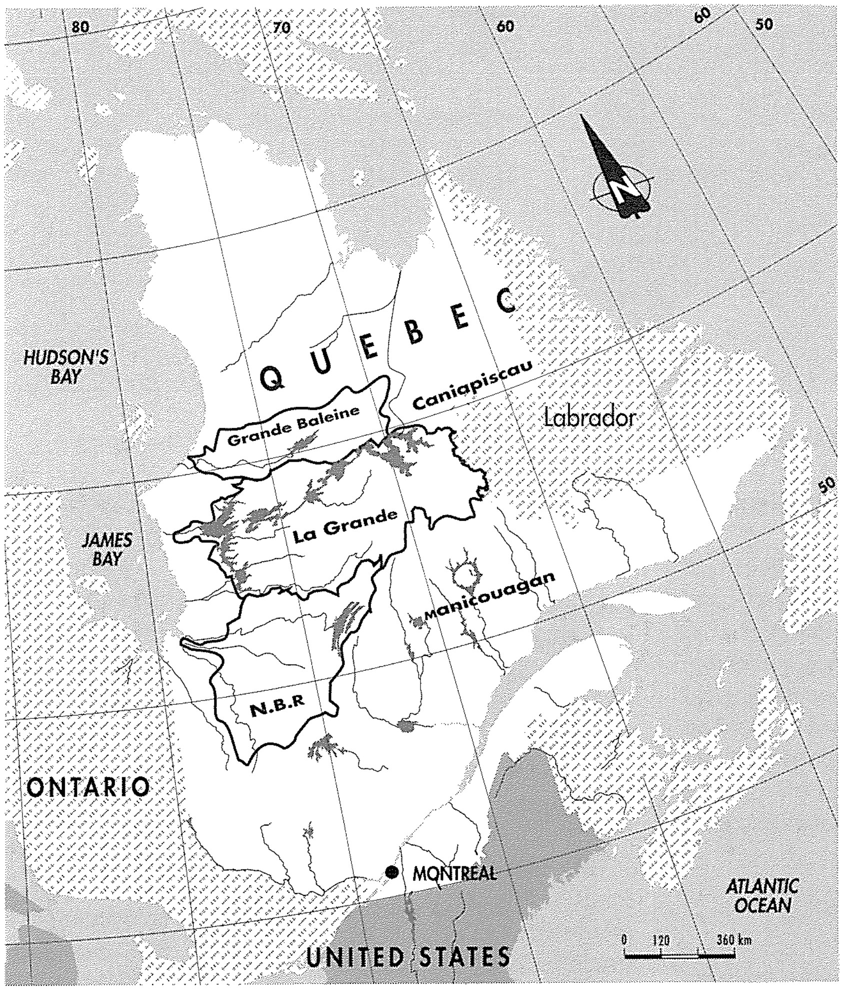

Fig. 1. James Bay Territory.

Société d'énergie de la Baie James (SEBJ)

The Société d'énergie de la Baie James (SEBJ), was formed in December 1971. It is a wholly-owned subsidiary of Hydro-Québec and was mandated to manage the hydroelectric development in the James Bay Territory. SEBJ management duties and responsibilities covered all aspects of the project, from obtaining permits, feasibility studies, detailed design supervision, scheduling, construction, cost control and surveillance during reservoir filling. Detailed design was done by consulting engineering firms following SEBJ design criteria. A Board of Experts reviewed all aspects of the project.

The La Grande Complex

The La Grande Complex involved the diversion of the Eastmain, Opinaca, Petite Opinaca and the Caniapiscau Rivers into the La Grande River (fig. 2). The development was divided into two phases:Phase I with 3 powerhouses and 10,282 MW and Phase II with 4 powerhouses and 4,940 MW (Table 1). A 5th powerhouse, Eastmain 1, will be completed at a future date. Some 312 embankment dams and dikes have been built, with a total volume of 167.3 million m^3 of fill, and measure 156.7 km in total length (Table 2).

Site Investigation

Since the project was located in a remote northern area, the investigation methodology and schedule had to be optimized, not only for economical and technical reasons but also because of climatic conditions, limited work season and difficult site accessibility.

Often during Phase I, manpower and equipment had to be air-lifted and site accommodations were very rudimentary. Thus the investigation program was optimized to strike a compromised balance between the need to obtain the information required for a safe and eco-

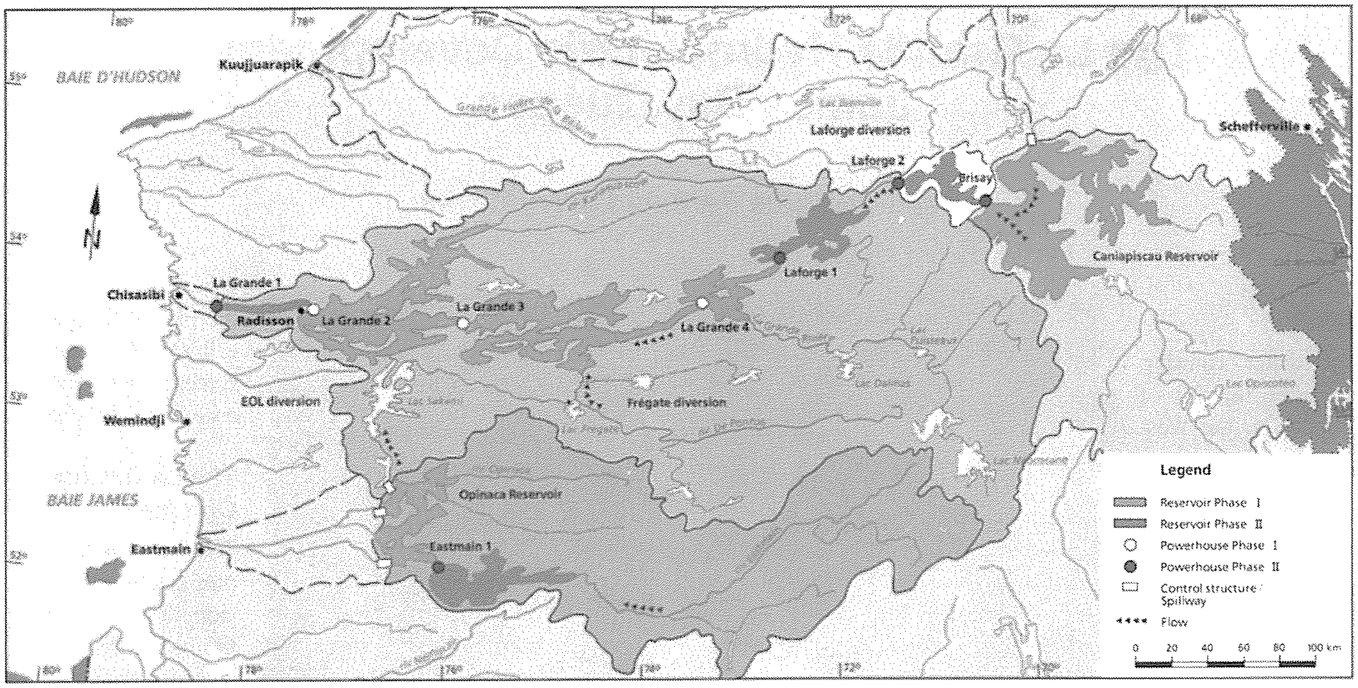

Fig. 2. Phases I and II of the La Grande Hydroelectric Development.

nomical design and the cost of the investigation.

The investigation work was carried out from 1971 to 1980 for Phase I, and from 1985 to 1991 for Phase II. The exploration costs including surveying, topography, hydrology and geological investigation, corresponded to less than 2% of the total cost of the project. About 3/4 of this cost was spent on logistics (transportation, remote camps, etc.).

Geological and Geotechnical Considerations

The project is located in the Precambrian Shield some 1,000 km north of Montréal. The main rock type is granite and granite gneiss of excellent quality. The region has been pereplained by the many glaciers that have eroded the rock surfaces down, generally, to sound rock, but at the same time caused relief jointing after their retreat.

The glaciers have left deposits of till over much of the surface and locally, glacio-fluvial deposits of silt, sand and gravel. The retreat of the last glaciation was followed by the invasion of the sea on the coast of James Bay where muskeg and deposits of marine clay can be found. To the south, the glacial meltwaters formed a large lake where varved clay was deposited.

The climate is cold, with temperatures reaching -50°C in the winter, with an average annual temperature of -4°C. Average annual precipitation is 827 mm, 40% of which falls as snow. Although the region is located in the discontinuous permafrost zone, no permafrost was encountered on the project.

The bedrock is of excellent quality for use as rockfill or concrete aggregate, as a foundation for earthfill or concrete structures and for surface and underground excavations.

The glacial moraine is a good foundation material, as well as providing the till for the impervious cores of the earthfill structures. The favourable geological and geotechnical conditions were used to the advantage of the project.

Rock Excavation

The rock quality allowed the rock walls of the excavations to be excavated vertically. Excavations are unlined, with the exception of penstocks. Permanent underground openings are pattern bolted with cement grouted bolts. The arches of temporary openings are wire meshed for safety during construction and ungrouted rock bolts are used only as required.

Water velocities were kept to 15 m/sec in temporary unlined tunnels, 2.5 m/sec in permanent tunnels, and as much as 25 m/sec in unlined open channels (La Grande 2 spillway).

The secret to the success of the rock excavations throughout the project can be attributed, of course, to the good rock conditions but also to the technical specifications, which were very specific in the manner in which the rock was to be excavated. Good blasting procedure and strict control produced good and stable rock surfaces.

Embankment Dams and Dikes

The embankments are of three types basically: homogeneous, zoned earthfill or zoned rockfill, depending on the foundation conditions and availability of construction materials (fig. 3). The impervious cores are made of a broadly graded till, which is generally very abundant throughout the region. The till must have a fines content of 15% or more passing the 0.080 mm sieve and have a maximum particle size of 300 mm. The till is placed in 45 cm thick lifts, compacted with 4 passes of a 50-ton pneumatic roller, and has a water content within the Standard Proctor Optimum (1%).

The filter (75 mm max) and transition (150 mm max) materials are made mostly of natural sand and gravel and respect the Terzaghi and Sherrard filter criteria, based on the gradation of the till matrix (i.e. on the till fraction passing the 5 mm sieve).

These two zones are generally made wide for easy mass placement and additional security (twice the width of the vibratory roller). The embankment shells are constructed with either quarried rock or sand and gravel.Other types of cross-sections were used when required for particular foundation conditions. Some examples of these specially zoned embankments are shown in figure 3.

	Powerhouse	Number of units	Power per unit (MW)	Installed capacity (MW)	Annual energy (TWh)	Commissioning date
PHASE I	La Grande-2	16	333	5,328	35.8	October 1979
	La Grande-3	12	192	2,304	12.3	June 1982
	La Grande-4	9	293	2,650	14.1	May 1984
	Total	*37*	--	*10,282*	*62.2*	--
PHASE II	La Grande-2-A	6	333	1,998	2.2	October 1991
	La Grande-1	12	114	1,368	7.3	March 1994
	Laforge-1	6	139.5	838	4.5	October 1993
	Brisay	2	223	446	2.3	October 1993
	Laforge-2	2	145	290	1.68	October 1996
	Eastmain-1	--	--	--	--	--
	Total	*28*	--	*4,940*	*17.98*	--
	GRAND TOTAL	*65*	--	*15,222*	*80.18*	--

Table 1. Powerhouse Energy Data.

Bedrock Foundations

Whenever possible, the impervious core and the filter zones of the embankments, are founded on bedrock, and the bedrock is treated with the utmost care. The bedrock foundations are thoroughly cleaned, and all loose and weathered rock removed. Great care is also taken in correcting unfavourable contours by removal or by concreting. The rock surfaces are then washed and dental concreted, shotcreted or slush grouted, depending on the rock conditions. The foundations are grouted systematically, using criteria which depends on the head of water on the embankment.

	Site	Number	Volume of excavation ($m^3 \times 10^6$)	Volume of fill ($m^3 \times 10^6$)	Length (km)
PHASE I	La Grande-2	30	5.38	48.03	26.6
	La Grande-3	70	4.75	35.85	27.0
	La Grande-4	11	2.41	33.42	8.7
	Caniapiscau	93	6.61	34.52	58.0
	EOL	11	1.18	6.68	11.1
	Total	*215*	*20.33*	*158.50*	*131.4*
PHASE II	La Grande-2-A	2	3.3	0.34	1.0
	La Grande-1	3	3.1	1.12	2.5
	Laforge-1	89	5.4	6.85	21.8
	Brisay	--	1.8	--	--
	Laforge-2	3	2.7	0.5	--
	Eastmain-1	--	--	--	--
	Total	*97*	*16.3*	*8.81*	*25.3*
	GRAND TOTAL	*312*	*36.63*	*167.31*	*156.7*

Table 2. Quantities - Dams and Dikes.

Overburden Foundation

For an impervious overburden foundation such as glacial till, the core was keyed into the foundation after the removal of the organic and pervious surface material.

For pervious foundations, treatment consisted of installing a complete or partial seepage barrier or cutoff, depending on the height and length of the embankment, and the nature and depth of the pervious foundation. Design philosophy was related to surveillance intensity and economical considerations.

Where technically and economically feasible, a complete water barrier was always preferred. Among the various positive cutoffs used during Phases I and II, best results were obtained with a core trench down to bedrock or a concrete panel wall anchored into the bedrock. This is due to the positive contact obtained at the rock contact using these two methods.

Slurry trench cutoffs, backfilled with soil-bentonite or soil-bentonite-cement, were less satisfactory because of the often imperfect cleaning of the rock interface at depth.

Seepage or high downstream pore pressures were often observed locally along the toe of embankments because of this imperfection. Complementary works such as toe loading berms, relief wells, additional instrumentation and surveillance were then required during and after reservoir filling where these types of cutoffs were used.

In a few cases, based on economical and technical conditions, upstream impervious blankets were used to reduce the seepage pressures and quantities to an acceptable level. This type of partial cutoff was always accompanied by some downstream drainage and toe protection, to control exit gradients and assure toe stability.

Innovations

The policy of SEBJ was not to "reinvent the wheel," so to speak, but to use proven methods for the design and construction of the project. The budget, schedule and quantity of work to be done dictated that the project was not to be used as a laboratory. When required, however, innovative design and construction methods were used.

For instance, the length of the underground powerhouses at La Grande 2 (16 units) and the La Grande 2A (6 units) made the use of rock shoulders practical for the support of the two (368 ton) cranes, resulting in significant economy from a cost and construction schedule point of view. Compared to the conventional column and beam alternative, the rock ledges offered the advantage of an early availability of the cranes for continuing the excavation and all concreting activities, a more uniform distribution of the very large crane loads in the supporting rock, and a reduction in the powerhouse excavation volume. These types of shoulders have been used previously at a few other sites but their use in Québec was new. It was felt that the advantages of using rock shoulders far outweighed the excavation risks and, with the good rock conditions, SEBJ adopted them.

The use of resin bolts, although limited was, in fact, abandoned altogether because of the problems associated with resin, long bolts and quality control. All permanent bolts are now hollow-stemmed, tensioned and grouted using a cement mix.

At La Grande 3, some of the available materials were very conducive to segregation when placed on the embankment. It was then decided to adopt special placement procedures to reduce or eliminate the segregation and, in parallel, to initiate a testing program in the field by

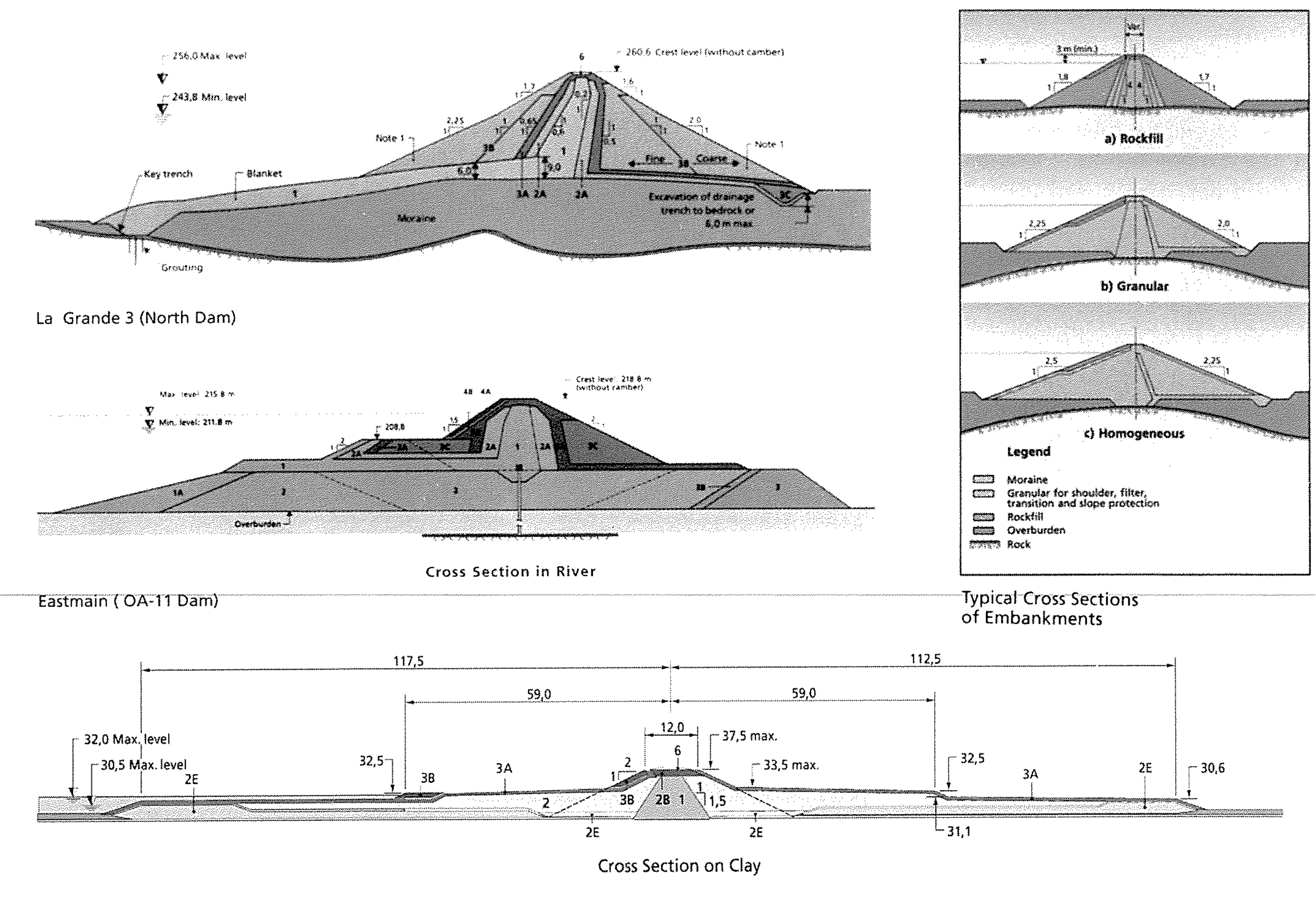

Fig. 3. Embankment Cross Sections.

developing a large-scale permeameter, in the form of a horizontal prismatic cell 1,52 m long with a 0.91 m square section. The testing program proved that the filter and transition materials, as specified, prevented particle migration at the core-filter and filter-transition interfaces and confirmed the field permeability and design assumptions.

Geotextiles were used sparingly and mostly in temporary structures (cofferdams) as a filter and a separator, or in permanent structures where their use was not really essential as a filter or drainage component. Some 400,000 m of geotextile was placed, mainly in cofferdams during Phase I and was useful in improving the working conditions and construction schedule, especially where suitable granular materials were scarce and where rockfill had to placed over saturated moraine foundations.

Testing of a geogrid at La Grande 1, as reinforcement for a muskeg foundation, showed that a slow rate of placement of the fill was more important then the presence of the geogrid itself.

A plastic concrete panel wall serves as a cutoff through a silty sand layer under the north dam at La Grande 1. The cutoff is 1030 m long and varied from 5.7 to 27.7 m in depth, designed as an impervious barrier that could withstand the deformation of the foundation of the dike.

Jet-grouting was used to block leaks, which occurred in the alluvium under the upstream and downstream cofferdams at La Grande 1. To take advantage of the diminished flows in the river during the filling of the La Grande 2 reservoir, the river at La Grande 1 was diverted into a diversion canal using rockfill cofferdams on the riverbed.

After dewatering between the two cofferdams, massive leakage occurred under the cofferdams and the area had to be flooded in order to preserve the stability of the cofferdams. A combination of a concrete panel wall and jet-grouting was used to cut off the pervious zone under the cofferdam embankments and the working area was then successfully dewatered. This was the first known use of jet-grouting and panel wall cutoffs under such severe conditions.

Problems of Interest

For a project of such magnitude, it can be said that the work generally went off "without a hitch." The management team quickly adapted to normal construction problems, such as cofferdam leakage or changed geotechnical conditions, to eliminate schedule delays and reimburse contractors equitably for justifiable claims as the work progressed. There were, however, three problems of note that are of interest to the geotechnical profession.

Firstly, during and even several years after reservoir filling, local crest settlement occurred at some dam sites in the form of a sinkhole, in the protective islands surrounding the instruments in the core, which varied in volume from a few cubic meters to as much as 30 cubic meters. At first, internal erosion and material loss through the rock foundation was thought to be the cause, but in fact had nothing to do with the settlement process. The settlement of the crest in the protective island locations occurred, because the finer till material of the islands was compacted with hand-held equipment rather than the mechanical equipment used for the core and the island material was therefore less compact. The till of the islands was placed on the dry side of optimum which also contributed to the settlement. During reservoir filling, or later when the core became fully saturated, the looser and finer material within the island collapsed and created a hole at the crest surface. The area around the sinkholes was excavated and rebuilt. The embankments have behaved well since.

The second problem of interest was the leakage, which developed under some of the La Grande 3 low head dikes near the end of the reservoir filling period. These dikes were built on deep pervious glacio-fluvial material and, because of their low height and the great depth of the foundation overburden, impervious upstream blankets were used in the original design to increase the seepage paths and thus control leakage and downstream uplift pressures. In fact, during reservoir filling, important leakage occurred through the foundation, in some cases even before the embankments were wetted, so that reservoir filling was stopped. Excessive leakage and downstream instabilities required prompt action. The LG-3 reservoir was lowered, extensive foundation exploration was done and a decision made to do remedial work. Depending on the depth of foundation to be treated, positive cutoffs were constructed through the upstream blankets or through the central cores of the dikes, either using the slurry trench method or concrete diaphram walls. Once these were completed, filling continued without incident.

The third problem of note was the degradation of some of the riprap protection of the Phase I embankments. Over the years after reservoir filling, riprap on several dikes started to deteriorate to a point were repairs where necessary. A study was undertaken, which included simultaneous wind and wave measurements, sizing of riprap and model testing at the National Research Council (NRC) in Ottawa. The main conclusion of the study was that fines in the riprap were gradually eroded by wave action causing deterioration, and loss of riprap.

The massive amount of information obtained during the riprap studies, allowed SEBJ to develop new parameters for design wave calculations and to prove that the minimum size of rock in a riprap controls the overall stability. It has been shown that by specifying fairly uniform riprap, fines have been eliminated, and it is easier for the field staff to control the size of riprap being placed. A guide to riprap design is now being written using this new philosophy.

Cost

The total cost of Phase I was $13.7 billion which includes transmission. Phase II costs $ 6.9 billion.

Both phases were completed as scheduled and under budget.

Cost reductions can be attributed to good management and also to rescheduling of the work in Phase II, which put the powerhouses into operation ahead of the original schedule. This reduced interest costs and was made possible by concreting the year-round, using heated shelters in the cold season.

Conclusion

The construction of the La Grande Hydroelectric Development was a major accomplishment. Located in a cold hostile climate, 600 km north of the nearest village, 1,500 km of road had to be built just to gain access to the various sites. The Board of Experts, who work on projects throughout the world, often commented that the La Grande project was one of the rare megaprojects completed on schedule and budget. Today the region supplies over 15,000 MW of power to the Hydro-Québec system.

The success of the project can be attributed to an integrated management team made up of personnel from participating firms, which provided the necessary flexibility, especially for recruiting the large number of qualified staff that was required.

Acknowledgments

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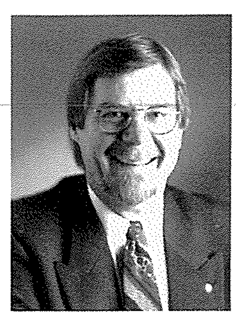
J-J. Paré has more than 30 years' experience in geotechnical studies and hydroelectric developments. Between 1973-87, as head of the Geology and Soil Mechanics Department of the James Bay Energy Corporation, he participated in the design, construction, monitoring, and safety analysis of over 200 embankment dams and dykes for the La Grande complex, Phase I in northern Québec. From 1988-93 he was involved in feasibility studies for hydroelectric development of several rivers in Québec. Since 1994 he has been a private consultant associated with dam safety in Canada and overseas.



JERRY LEVAY earned a technical diploma from the Provincial Institute of Mining in Ontario, in 1959 and a degree in geological engineering from the Michigan Technological University, 1966.

Mr. Levay has participated on hydroelectric projects for varies companies such as SNC, Terratech, Hydro-Québec and Hydro-Québec International on the Manicouagan-Outardes Complex, Première Chute, Churchill Falls, Three Gorges and Longtan in China. For the last 25 years, he has been involved in Phases I and II of the La Grande project and is manager, Engineering and Environment, Société d'énergie de la Baie James (SEBJ).

James Bay Complex. LG - 3. South dam (Main dam).(Photo credit:Hydro-Québec).

Manicouagan-Outardes Complex Outardes - 4. Main dam and powerhouse. (Photo credit:Hydro-Québec).

James Bay Complex. LG - 2. Main dam and spillway. (Photo credit:Hydro-Québec).

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