Geotechnical Instrumentation NEWS

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John Dunnicliff

Introduction

This is the thirty-eighth episode of GIN. There's one article about instrumentation this time, and a reprint of a lecture that doesn't really belong under the GIN heading, so we've given it the heading "Special Lecture".

Errata

I wonder how many of you noticed. The photo of the "Norwegian Geotechnical Institute's Vibrating Wire Strain Gage Music Machine", in my previous GIN column, somehow lost the last three words of its title. Sorry Elmo! Blame the publishing software.

A New Strain Gage for use on Geotextiles

The following article by Aasen and Holtz tells about the development of a strain gage that can be used to monitor strains of up to 80% in geotextiles. If proven in a field situation, it seems to me that this is a better way to go than the usual method, in which long gage-length electrical resistance strain gages are glued to the geotextile. More straightforward, less expensive, and larger range. Comments from anyone?

Two Pungent Quotations

Two colleagues recently wrote the following in e-mails to me:

"On the most basic level, I believe the most important thing in installation of instruments is to get the right answer. Costs are secondary. I've found through experience that it pays to be sure of every single installation and not to cut corners. It's cheaper and more diligent in the end. If you always keep this approach, you won't second guess the instrument reading."

and

"Based on our experience to date, we would have serious concerns about ever constructing a new embankment dam with any intrusive instrumentation in the core zone."

Yes, yes and yes.

The Grout Tests

Yes, I know that I promised that some test results (lab testing of cement-bentonite grouts to determine strength, permeability, compressibility and volume stability) would be in this episode, but the test program has turned out to be less straightforward than we thought. Please be patient – we'll get there in the end!

Laurits Bjerrum

Laurits Bjerrum was the first Director of the Norwegian Geotechnical Institute (NGI), from 1953 until his untimely death in 1973. A book *"Laurits Bjerrum – more than an engineer"*, has just been completed, edited by Kaare Flaate, Elmo DiBiagio and Kåre Senneset. A review of the book by Ralph Peck will be published in the June 2004 issue of this magazine. One of the sections of the book, a lecture given in 1965 at Loyola College in Baltimore, is reprinted here, starting on page 34. I picked this section because it illustrates so very well the wisdom and communication skills of Bjerrum, and is understandable by non-engineers – might your spouse read it?

Four meaningful quotes from the book:

1. …the road to be followed by NGI…was outlined in a lecture given…in 1958…:
   - Division [at a research institute] into consulting and research always kills the research. Consulting is necessary to learn where the problems are and to collect experience.
   - Other institutions suffer from a concentration of interest. Don't give too much weight to a certain field. Spread uniformly, never afraid of starting up where there is no interest.
   - Keep consulting at a reasonable level, concentrate work on a few difficult jobs, maintain good relations with the private sector.
   - Follow up on jobs; find out what happens afterwards.
   - Let NGI be known as a place where reliable good work is done within a wide field.
2. It is most likely correct that on the day Our Lord distributed ground conditions among the different countries, Norway was standing at the end of the queue.
3. It is not wrong to say that NGI has been one of those, which went in front in the world and showed the way in this field [of instrumentation and measuring techniques].
4. [This is a letter from the Planning

Office for Oslo Subway System suggesting contractual arrangements for "extended geotechnical assistance"]. *According to the arrangement with engineer Vold, our office has prepared a draft agreement. This is enclosed for your examination prior to sending it to the Office for Geotechnics. Maybe the draft is too much businesslike in its form, but I think it covers the tasks that should be contained in a list like this. The frame of the agreement will have to be elastic and we are at the end talking about a sort of "gentleman agreement" since one evidently cannot include paragraphs for all situations that come into being. Please give me your opinion on the draft before it is sent to the Office for Geotechnics – especially if you find it too lengthy and too detailed.* [The editors add: "We think that this 'Gentleman agreement' between the consultant and the representative of the owner tell us a lot about the persons involved. It could only take place in an environment of trust and high professional integrity"].

Enquiries about availability of the book should be addressed to *Wenche Enersen at NGI, we@ngi.no.*

Closure

Please send contributions to this column, or an article for GIN, to me as an e-mail attachment in MSWord, to *johndunnicliff@attglobal.net, or by fax or mail: Little Leat, Whisselwell, Bovey Tracey, Devon TQ13 9LA, England. Tel. and fax +44-1626-832919.*

Mubarik! (India). No, not Egypt.

A New Geotextile Strain Gage

Jostein Aasen
Robert D. Holtz

Abstract

Our objective was to develop a strain gage for geotextiles that could measure large strains and at the same time avoid reinforcing effects. If possible the gage should also be relatively inexpensive, simple to install, and easy to read. This article describes the developed instrument, called the Modified Electrolytic Strain Gage (MESG), which consists of an elastic butyl rubber tubing containing an electrolytic solution with known electrochemical properties and sealed to electrodes at each end. When the tubing is strained, the geometrical properties of the tubing change, which causes a change in the resistance of the contained electrolyte. The gage is powered by low-voltage AC, and by measuring the change in voltage drop across the MESG using a multimeter, a corresponding change in resistance can be calculated. Resistance-strain calibration curves were determined in-isolation and compared with the theoretical behavior; repeatability and sensitivity of the gages were also observed. To investigate the applicability of the MESG as a geotechnical monitoring instrument, gages were embedded in a triaxial soil specimen and subjected to confining pressures. Measured MESG strains compared well to the axial strains observed in the triaxial cell. Then the MESGs were attached to wide-width (ASTM D 4595) geotextile specimens and tested in tension. The strains measured compared favorably to the machine cross-head tensile strains. The research showed that the MESG can measure strains in excess of 70 to 80% without major discrepancies, and the gages did not appear to alter the shape of the tensile load-deformation curves. Thus the MESG should meet all the requirements for a strain gage suitable for use on geotextiles, both in the laboratory and in the field. It also can be used for measuring in-soil strains.

Introduction

This article briefly describes the MESG, the theory behind its function, and its calibration. The results of tests on the gage confined in soil as well as attached to wide-width tensile test geotextile specimens are also presented. Additional details on the development of the MESG, and additional test data are given by Aasen (2000) and Aasen and Holtz (2003).

Description of MESG and Theory

The MESG consists of the following components:

- Butyl rubber tubing with an inside diameter (ID) and outside diameter (OD) of 1.6 and 3.2 mm, respectively;
- Two stainless steel electrodes 3.2 mm in diameter; and
- Electrolyte, a solution of 0.1 M sodium hydroxide (NaOH).

The MESG is shown in Figure 1.

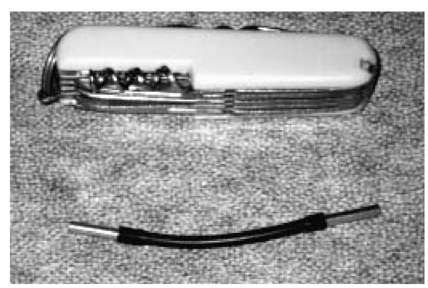

Figure 1. MESG. The pocketknife is for size comparison.

The butyl rubber tubing containing the NaOH electrolyte with the two stainless steel electrodes is really a variable resistor. From electrochemical theory, the resistance can be determined by the following equation:

$$R_i = \frac{1}{K} L_0 \frac{(1+\varepsilon_i)^2}{A_0} \qquad (1)$$

where R_i = resistance of the MESG after straining (ohm), K = conductivity of the electrolyte (0.022 $ohm^{-1}cm^{-1}$), L_0 = initial distance (i.e. prior to straining) between the electrodes (cm), ε_i = strain, and A_0 = initial cross-sectional area of the electrolyte (i.e., the ID of the rubber tubing). As can be seen from Eq. 1, when the MESG is strained, the resistance of the contained electrolyte changes, and the shape of the corresponding resistance-strain curve should follow a polynomial to the 2nd degree. In use, the MESG is connected in an electrical circuit in series with a 1 Mohm resistor, and a current generator applies a 1V AC excitation to this circuit. A multimeter was used to record the voltage drop across the MESG. From Ohm's law, the voltage drop measured across the MESG is converted into an electrical resistance that can be correlated through calibration to the strain experienced by the MESG.

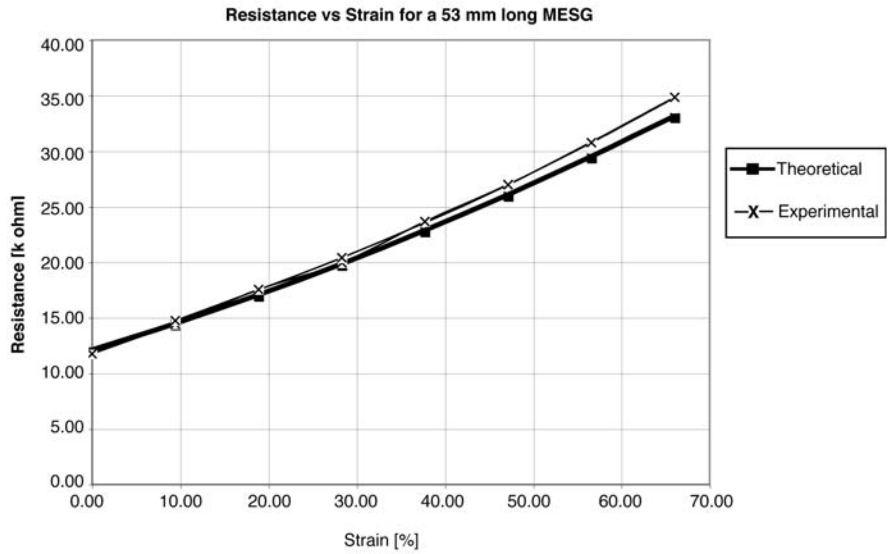

Figure 2. Theoretical and experimental resistance vs. strain results for a 53 mm long MESG.

Calibration

In order to validate the concept of the MESG as well as to calibrate it, the sensor was first tested in tension in air. The change in resistance as the MESG was strained was compared to the theoretical resistance (Eq. 1). Figure 2 shows these results for a 53 mm long MESG.

The results indicate that in general the experimental resistance of the MESG was slightly larger than the theoretical resistance. This difference may be due to the following:

- The rubber tubing might not have been completely saturated with electrolyte;
- The strain readings of the MESG were manually taken, which could result in some error, although this error should be random.
- The theoretical model neglects the electrolyte-electrode interface;
- The theoretical model assumes that the rubber tubing deforms uniformly when strained, i.e. that the cross-sectional area of the tubing deforms uniformly across its length.

See Aasen (2000) and Aasen and Holtz (2003) for additional discussion on these issues. The sensitivity of the MESGs depends on its nominal length, strain, and the sensitivity of the multimeter used to measure the voltage drop across the MESG. Our multimeter could measure a voltage change of 0.01mV. This sensitivity corresponded to a strain sensitivity of 0.038% for a 53 mm long MESG at 0% strain and 0.026% sensitivity for the same MESG at 50% strain. Other length gages had similar sensitivities.

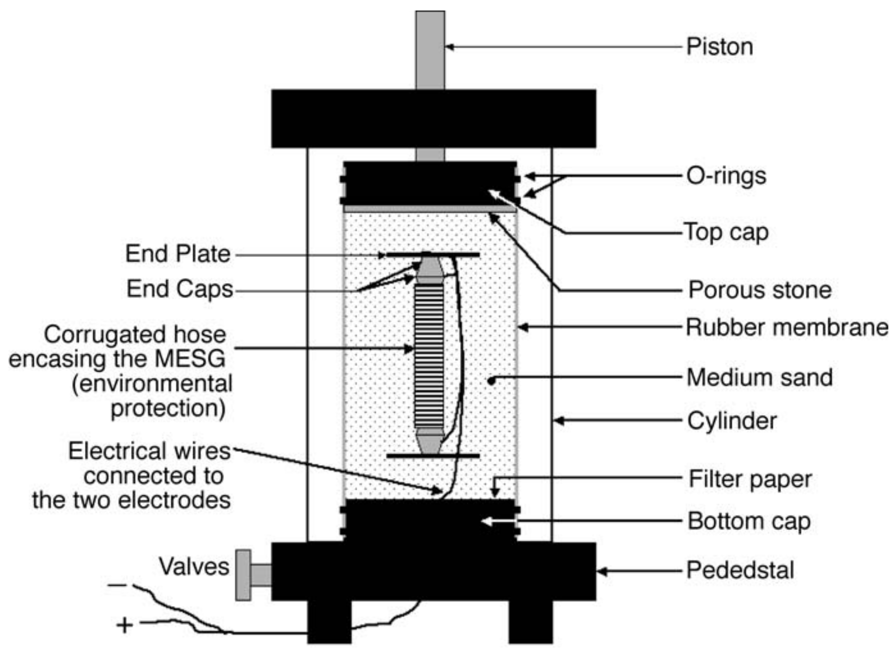

Figure 3. Cross sectional view of a triaxial specimen with embedded MESG.

Testing in Soil

To investigate its applicability as a soil strain gage, we placed some MESGs in a triaxial soil specimen. We were interested in learning whether the presence of the MESG reinforced or weakened the soil, how the strain measured by the MESG compared to the total strain of the soil specimen, the flexibility and operating strain range of the MESGs; and what effect the soil confining pressures had on the MESG output. Prior to

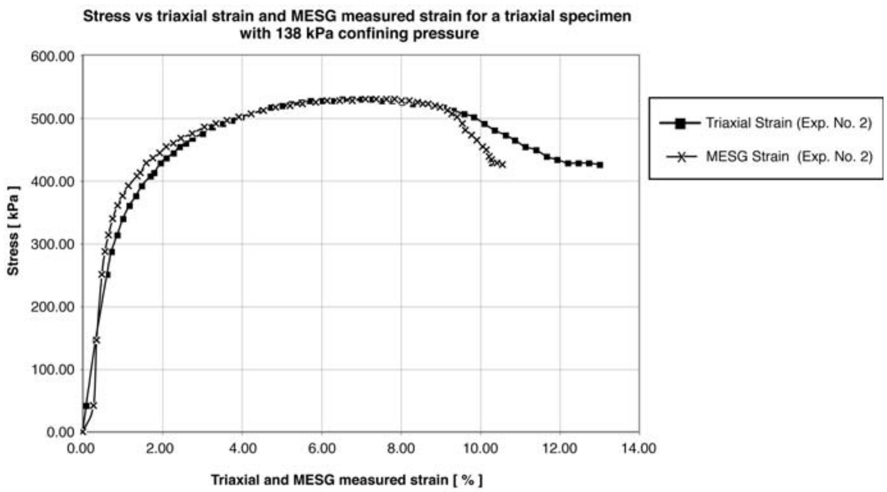

Figure 4. Stress vs. strain and MESG measured strain for triaxial specimen at 138 kPa confining pressure.

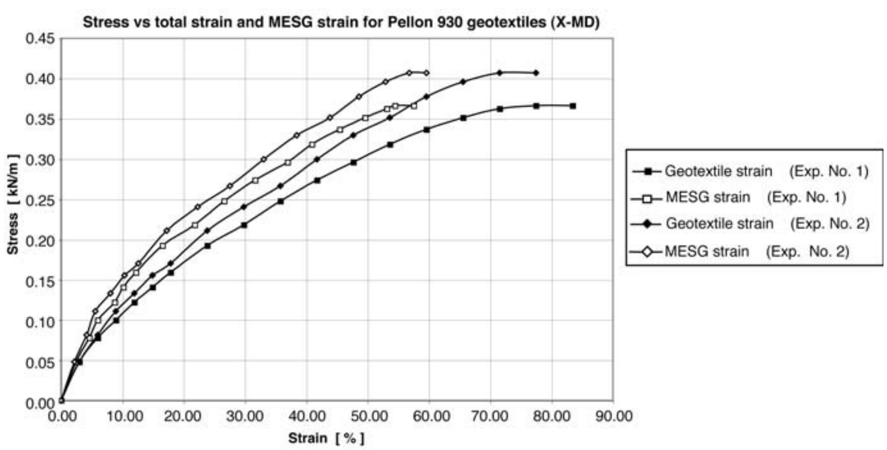

Figure 5. Stress vs geotextile strain and MESG measured strain for Pellon 930 geotextiles (X-MD).

burial, the MESGs were encapsulated in a flexible corrugated plastic hose with two end caps and end plates, as shown in Figure 3 (see also Figures 6 and 7 of Aasen, 2000, and Figure 3 of Aasen and Holtz, 2003). The soil in the triaxial specimens was a medium sand and confining pressures ranged from 69 to 207 kPa, both with and without the MESG embedded. The specimens were loaded axially, and during shearing of the specimens with MESGs embedded, the MESG measured strain was recorded and compared to the soil specimen strain as measured by the mechanical dial indicator on the triaxial cell. As shown in Figure 4, these strains agreed quite well with each other. Additionally, no effect on the MESG output due to soil confining pressure was observed. The MESGs were able to measure soil strains up to 13% (at which point the triaxial test was terminated) without any loss in output.

MESG on Geotextiles

To verify the applicability of the MESG as a geotextile strain gage, we wanted to know whether the MESG had any effect on the load-deformation characteristics of the geotextiles, how the geotextile strains measured by the MESG compared to the strains measured by other means, and the operating strain range of the MESGs. Consequently, MESGs were attached with nylon thread and thin plastic plates to a variety of non-woven geotextiles. Then the specimens were tested in a wide-width tensile (WWT) testing apparatus according to ASTM D 4595. Figure 5 shows the results from these tests, and as can be seen, the strains measured by the MESGs were on the average 70-90% of the cross-head geotextile strain as measured by the mechanical dial indicators attached to the clamps on the WWT apparatus.

The strains also appeared to depend on the geotextile strength. Geotextiles with similar strengths in the machine and cross machine directions seemed to provide a better base for the attached MESG, and their MSEG strains were closer to the total geotextile strain. It should be noted that the geotextile strain in the WWT is not expected to be uniform across the geotextile specimen, and some discrepancy should be expected. Additionally, these tests were preformed without soil confinement. Finally, the geotextile specimens were tested until failure or rupture occurred, in order to evaluate the strain range of the MESGs; the results indicated that the MESGs were able to measure strains up to 70-80% without any deterioration in the output of the MESG.

Final Comments

This research shows that the MESG can be used as a geotextile strain gage. Additionally, with proper environmental protection, the MESG can also be embedded in soil and used as a soil strain gage. The advantages of the MESG are:

- Flexibility and ability to measure large strains;
- Low elasticity modulus and small physical size (suggesting that its presence has little effect on the surrounding environment);
- Easy to attach to geotechnical installation;
- Easy to operate;
- Easy to apply environmental protection; and
- Economical

However, it is important for the MESG to remain in a strained condition throughout the entire process. The MESG as described in this paper was calibrated in order to research the feasibility of the instrument. We hope that we or others will have the opportunity to examine the performance of the MESG in field conditions, when attached to geotextiles and embedded in soil, and that the results will be reported in a future issue of GIN. Please contact the authors if you would be interested in further development of the instrument.

Acknowledgements

The first author would like to thank the Valle Scholarship and Scandinavian Exchange program for supporting his studies at the University of Washington. Discussions with Professors M. Afromowitz, S. Kramer, and P. Arduino were very helpful to various phases of this research.

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SPECIAL LECTURE

On Being a Civil Engineer

Lecture at Loyola College, September 16, 1965

Laurits Bjerrum

This lecture has been abstracted from the new book, "*Laurits Bjerrum – more than an engineer",* edited by Kaare Flaate, Elmo DiBiagio and Kåre Senneset. A review of the book by Ralph Peck will be published in the June 2004 issue of this magazine.

Laurits Bjerrum was the first Director of the Norwegian Geotechnical Institute (NGI), from 1953 until his untimely death in 1973. The following introduction is by Elmo DiBiagio.

Bjerrum was a Gifted Lecturer

One of Laurits Bjerrum's tools for dissemination of knowledge was lecturing, and he used this tool frequently and with great skill. Bjerrum generally lectured in one of two ways depending on the nature of the occasion, the subject matter being presented, and the makeup of the audience in front of him.

Bjerrum was famous throughout the world for his highly motivating scientific lectures. These were seriously and enthusiastically delivered in a style that never failed to capture and hold the attention of his audience. These lectures quite frequently contained major contributions to our understanding of soil mechanics and foundation engineering; consequently many of them have come to be regarded as classical reference works in the literature.

Bjerrum's other method of lecturing can be best described as the laugh and learn approach, and he was indeed a master of this technique. He had a unique ability to integrate technical details with humorous anecdotes or personal experiences and present these in a fascinating and entertaining manner and still make his point. This method of holding lectures was one of Laurits Bjerrum's trade marks, and we believe it was the type of lecture he preferred to give.

He also kept an accurate record of the date, place and audience of all his lectures. The list includes 334 lectures in 20 countries. He also kept most of the original manuscripts. These fill 22 bound volumes and occupy 1 meter of shelf space in the NGI library.

The editors have selected for publishing in this volume two lectures that have never been published before. The first one is a lecture he held on September 16, 1965 at the Fall Honors Convention at Loyola College in Baltimore, Maryland when he was awarded an honorary degree from Loyola.

He Deeply Appreciated the Honorary Degree

Before staring his prepared lecture at Loyola College, Bjerrum commented that he represented a small group of people employed at a small research institute located far away in a small country, and now he was at a small college in a big country to receive a very big award. He referred to Loyola College as a small college but he went on to say that the size of an institution is not necessarily the best measure of how successful it is. What counts is the value to society of the goals it has established and whether these have been achieved or not. For this reason, he added, he was particularly honored that his first honorary degree was to be bestowed by a small college known not for its size but for its high educational standards.

Some years before there were some lively discussions in the United States about the adequacy of the current methods of teaching engineering. Inspired by this debate, Loyola College introduced a new course of undergraduate study called "Engineering Physics" designed to give engineers, at the undergraduate level, a more theoretical background than commonly included in traditional engineering curricula at the time. This is perhaps why Laurits started his lecture by differentiating between the work of a scientist and the work of an engineer.

The manuscript for the lecture did not have a title. The title of the lecture, as well as the subtitles, have been composed by the editors.

On Being a Civil Engineer

First of all, may I express my deepest appreciation for the honour conferred upon me by the Faculty of Loyola College. I thank the President, the Very Reverend Sellinger, for the extremely kind remarks he made about me. I feel very touched by what he said.

I would not be honest if I did not admit – quite frankly – that I am extremely happy for this unexpected recognition of my work. But I shall also have to admit that when I receive this honorary degree I consider myself as a deputy, only representing a group of colleagues and close friends, with whom I have cooperated so intimately that it is impossible to distinguish their contribution from mine.

There is a special reason why I am happy for what has happened today. Many of you may not be aware how unusual it is that the work of a civil engineer is acknowledged. In contrast to the scientists, who are the featured heroes of our generation, the civil engineers have gradually been reduced to playing a very modest role in the community they serve. Therefore, you will understand how surprised I was when I received the letter from Father Beatty in which he told me about the decision of the Board of Trustees of Loyola College, and how much I appreciate that a non-technical College with the highest human and idealistic goals has decided to award one of their honorary degrees to a simple civil engineer.

The Scientist is the Hero of our Time

I mentioned that the scientist is the hero of our time. In illustrated magazines, on TV, and in newspapers you will find his portrait, sitting in a white coat behind his microscope or in front of a computer. Behind the gold-framed glasses, the eyes of our hero scientist radiate harmony, and we get the impression of a person who is living in an elevated isolation of superiority. No wonder that our young high school students are attracted by this picture when planning their future career.

In contrast to the scientist pictured in the midst of his work, the civil engineer is in public opinion identified with the end product of his work. He is the per son who takes care of the existence of the water in the bath, the electricity for the shaver, the highways and the bridges that shorten the distances. He is more or less reduced to "a plumber" of our society, fighting with dirt and water, working with primitive tools such as bulldozers, reinforcing steel and concrete. No wonder that this picture – as seen with the public eye – does not attract our youngsters. The unfortunate consequence of this is that the number of civil engineering students for some years has steadily decreased in this country.

The Role of a Civil Engineer

Before World War II the milestones which measured the progress of our civilization were the important civil engineering accomplishments such as the George Washington Bridge, Hoover Dam, the skyscrapers of Chicago and New York, the Trans Siberian Railway, and so on. Today the milestones are represented by the gigantic computers, the satellites, the atomic reactors and similar scientific products.

No one will object to this state of affairs, least of all the civil engineers who are still happy with their work, irrespective of public interest. The reason is, of course, that neither public interest nor the nature of the end products of the work count. It is the growth and the act of creation which are the essence of life.

The most logical continuation of this talk would obviously be to give a general analysis of what the term engineering stands for and to describe the type of work involved. But, instead of involving myself in abstract speculations, I would prefer to describe the work of a civil engineer by a specific example from my own field.

The Challenges are Numerous

With your permission I will take you all with me on a short trip to my home country, Norway. Somewhere near Oslo we find ourselves on a green slope descending gently towards the Oslofjord. At the site we are met by the director of a nearby factory, and he explains in great detail that he is going to expand his industry and plans to build a 5-storey building on this spot. He is now interested in knowing what type of foundation to select for the building, requiring that the settlements should be so small that they will influence neither the structure itself nor the sensitive machinery it is going to contain. After entrusting this assignment to us, the director leaves the site.

As experienced engineers we do not start immediately to dig holes in the ground. No, let us enjoy the fine sunshine and try to project ourselves into this new situation by walking leisurely around in the surroundings. We stop at the old buildings of the factory. Our trained eyes will immediately detect that they must have experienced considerable settlements. The walls are tilting to the left and to the right and we discover cracks over the doors and windows.

A little further down in the landscape, near the fjord, we find traces of an old landslide and in a conversation with an elderly gentleman we are fortunate enough to meet, we are informed about its history. It was the day before Christmas Eve some twenty years ago that a small slide occurred in the bank towards the stream. Within a few minutes this first slide was followed by a series of rapidly occurring slides which progressively destroyed a huge area including a small farm. The most peculiar feature of this slide was, however, that as the slide masses were involved in the movement they became completely liquid, and they flowed down the valley carrying with them the remains of the farmhouse, a cow and a horse.

A Small Task but a Big Problem

Gradually, we are learning that the assignment we have accepted is considerably more difficult than it seemed to be in the beginning. Within a couple of hours we become intensely fascinated by the challenge, and we are impatient to find out what type of soil we are going to find at this site.

Consequently the next step will be to explore what is below the surface of the site. We will organize a series of borings and, although I shall spare you the details, the engineer will carefully follow this work which involves more problems than one should think.

One of the purposes of the borings is to get hold of some samples of the soil and, obviously, they should be as undisturbed as possible. In order to have the full benefit of your assistance on this job, I brought with me a sample of the material found in the boring. It is a grey clay. If we press a finger against the clay, we feel that it has a certain strength. But we also discover that the slightest disturbance is enough to cause a radical change its consistency. When the clay is remoulded, a most dramatic reduction in strength occurs, leaving us with a liquid with a consistency like a heavy oil. It is this property which has given the clay its name: Quick clay. Our thoughts return for a moment to the old man's description of the landslide, and we begin to understand the details of the slide, with liquid clay descending down the valley.

Let us Look into the Details

Before putting the clay aside, let us just take a look at it in a magnifying glass. We observe that it consists of small flake-shaped mineral particles with the pores in between filled with water. Here and there we discover small shell fragments and micro-fossils which we can identify as species which are today found in the big arctic oceans.

In order to find a solution to the mysterious problem of quick clay, let us climb a nearby rock outcrop and relax in the sunshine for a while. When sitting here, we will use our imagination in an attempt to form a picture of how this clay came into existence.

If we had magic eyes and could see what was below the ground surface, we would discover that this peculiar clay is present not only at this site we just studied. Actually, hardly a single site along the Oslofjord exists where we do not run into this type of clay. If we look further, we will discover wide areas in eastern Canada, Sweden and Finland where quick clay is dominating. All these areas have in common that they were completely covered by the huge ice sheets of the last ice age, the Pleistocene.

The effect of the enormous glaciers, which covered the country during the Pleistocene was tremendous. Soils, stones and loose rock were, crushed, ground and pushed down the valleys. The weight of the glacier was actually so great that it caused a substantial depression of the occupied areas. At the end of the glaciation, the city of Oslo, for instance, was located at least 800 to 900 feet lower in elevation than it is today.

Great Changes Have Taken Place

In the subsequent period with warmer climate and a consequent withdrawal of the glaciers, soils and crushed rock were carried to the ocean by rivers of melting water and deposited on the seafloor in front of the retreating glaciers. Around the boundary of the ice sheet, heavy deposits of clay were formed, and as they were laid down in the ocean, they became marine clays containing shells and fossils of animals living in salt water.

Simultaneously with the melting of the glaciers, the underlying rock was unloaded, resulting in a land elevation. Around the Oslofjord the isostatic uplift amounts to about 700 feet relative to the present sea level and, actually, it still takes place at a rate of about one foot per century.

Because of the land elevation the late-glacial clay deposits rose above sea water level and today they form the subsoil of a major part of the most populated areas around the Oslofjord. When the clay deposits came above sea level they changed environment and became for instance exposed to a slow flow of freshwater leading to a gradual exchange of the saltwater, initially confined in the pores of the clay, with freshwater. This leaching is responsible for the peculiar properties of the quick clay. If some salt is added to the clay we can bring it back to its original conditions and as the salt is mixed with the clay and is dissolved we observe a substantial increase in strength.

So far for the Geology. We now understand why quick clays are found only in areas in Canada, Sweden and Norway which after the last glaciation were raised above sea level by the isostatic uplift. And we can appreciate why exactly these areas suffer from landslides of the type described by the old man. This example is only one out of hundreds or thousands. One of the biggest slides we know of occurred in Norway in 1893. About 70 million cubic yards of clay became involved in the slide and flowed as a liquid down the valley. 111 persons lost their lives of whom the greater part drowned in a tremendous lake formed by the liquid clay.

Now, to Take Care of the Factory

Let us return to our factory and its foundation. The next step is to bring into the laboratory a number of representative samples in order to measure the mechanical properties of the clay. I do not need neither to emphasize that the samples ought to be undisturbed, nor to explain what a delicate job it is to handle such a sensitive material in the laboratory.

As the settlement of the factory is one of our main concerns, we will first of all study the compressibility of the clay. A sample is carefully mounted in a steel cylinder and placed on a base disk made of a porous stone. A piston fits exactly in the cylinder and by loading the piston we can subject the clay to an axial stress.

When applying the load in small steps we discover that the clay is relatively incompressible as long as the load on the sample is smaller than the overburden pressure the clay carried in the field. As soon as the load exceeds the previous overburden pressure the compressibility increases dramatically. We may confirm this finding by subjecting the sample to a series of unloadings and loadings, all showing that the compressibility of the clay is small until the load exceeds the maximum pressure the clay once carried. We might conclude that the clay structure has a sort of memory, remembering the preload it was once subjected to.

Laboratory Tests Give Important Information

The behaviour we have been observing in the laboratory is very characteristic for plastic clays and, indeed, we can immediately make use of it in practice. The factory which we are going to build has a basement. A substantial volume of clay has, therefore, to be excavated before the construction can begin. As a result of this excavation the clay will be unloaded by a pressure equal to the weight of the removed soil. As the construction of the factory proceeds, the load on the clay will gradually be increased. However, as long as the load is smaller than the weight of the excavated soil the settlements will be small, and it is when we first exceed this value that settlements become a problem.

The settlement problem can thus be completely eliminated by modifying the design of the building. We can simply increase the depth of the basement so much that the weight of the excavated volume of soil equals the total weight of the building. In this way we obtain a solution which we might call a “floating foundation”.

The Solution Imposes a New Problem

We were thus fortunate enough to find a reasonable answer to the settlement problem. But the solution we selected imposes on us a new problem. Is it possible to make an excavation as deep as required in clay as soft as this quick clay without causing deformations and disturbances of the clay? There is not the slightest doubt that if the clay is disturbed its compressibility increases dramatically. It is therefore a necessary condition for the success of a floating foundation that the clay is left undisturbed during the excavation work.

And that this problem is a serious one can be confirmed by most Norwegian contractors. It has happened very frequently in an excavation that a contractor, much to his surprise, has been unable to dig deeper, no matter how much clay he excavated. The clay was simply so soft that the bottom of the excavation rose at the same rate as the clay was removed.

Whether or not such a bottom heave failure will occur in an excavation depends on the shear strength of the clay. We must determine the shear strength on undisturbed samples in the laboratory or by using special equipment, we can measure it directly in the field.

In order to proceed from the measured shear strength to the critical depth of an excavation at which a bottom heave failure will occur, we need a piece of theory. This theory will tell us the magnitude of the shear stresses which exist around an excavation. From a comparison of the shear stresses and the shear strength of the clay we can then evaluate the safety factor of the excavation.

Among the tools which are needed in civil engineering, applied mechanics plays a most important role. The design of a large suspension bridge for instance, requires the solution of very intricate mathematical problems in order to determine the stresses and the strains on the individual members of the bridge. In the design of steel and reinforced concrete structures, such theoretical computations can be used directly as a basis for the design. The properties of these materials are well known and can furthermore be controlled during the construction, and one can, therefore, rely upon the fact that the assumptions on which the theoretical computations are based are in agreement with the actual conditions. But in many cases – and first and foremost in foundation engineering – the conditions are not so favourable.

Theory is a Guide for Engineering Judgment

Soil is a product of nature composed of particles ranging from gravel and sand to highly colloidal clay. It is placed by rivers or glaciers or sedimented in water, frequently in a very erratic way. In addition it is beyond our possibilities to obtain more than a very crude picture of the configuration of the soil layers. It goes without saying that when we deal with soils, the assumptions which are put into a theory are associated with considerable uncertainties. Even under the most favourable conditions a theory can serve only as a guide for an engineering judgement. There is consequently no need for refined theories in soil mechanics and – with slight exaggeration – any theory which cannot be derived on the back of an old envelope is of very limited value.

Once again I got distracted from our assignment on the foundation of the Norwegian factory. So far, we have been successful, as we have reached a solution with a floating foundation by increasing the depth of the basement and with a simple piece of theory we have just found that the excavation can be carried out without risking a bottom-heave failure.

But this is only one out of several possible solutions. Another solution may be to drive piles to a firm resistant layer at greater depth and a third one to preload the site in order to "take the settlement out of the ground" before the structure is built.

All these solutions must now be studied and their advantages and disadvantages compared. Of special interest are, of course, the costs and the solution which is finally selected is that which for the minimum cost presents a satisfactory and adequate solution to the problems. Some people may find it repulsive that the costs are of such dominating factors in engineering. Actually, I believe costs play an equally important role in most professions. For an engineer it is a direct part of the challenge. Any person of average intelligence can build a dam across the Colorado River if costs were of no concern. It was the challenge of the engineers who built the Hoover Dam to design and construct a dam which showed an adequate safety factor at a minimum of costs.

The next phase of our work is on behalf of the owner to follow the construction of the foundation. In cooperation with the contractor we shall plan all details of the work. Nothing is left to chance and during construction every opportunity is used to check that the assumptions on which the design was based are really fulfilled.

As soon as the foundation raft is poured and the building is well above ground level, our work is finished and we can leave the job. The results of all our efforts are now deeply buried below the surface of the ground. If everything goes well, our contribution to this job will soon be forgotten. No glamour is involved in the job of a foundation engineer, and it would be an exception to the rule if he is remembered with an invitation to the inauguration of the factory. However, I hope this analysis of an engineering job has illustrated that it is the act of creation and the challenge of the job which makes life interesting and that the only reward worth while in our own consciousness of having done a satisfactory job.

There are no Short Cuts in an Engineering Analysis

Finally, we have got the factory built and our assignment has come to an end. Some of you may think that we had to go a long way in order to reach a solution that simple. This may not sound unreasonable. But, in fact, there are no short-cuts in an engineering analysis. An engineer will by himself have to work through all the fundamental principles of the problem in order to be sure that there are no weak points in the solution.

Others may postulate that it is an example of ridiculous foolhardiness to build a factory directly on a clay deposit which is so soft and so quick as the material I have demonstrated to you. For an engineer the word courageous does not have a real meaning. He speaks about good or poor engineering and – in spite of what we call it – it is a matter of fact that in the past decade a great number of buildings have been constructed with very successful floating foundations on clays similar to the sample I showed you.

I hope with this example to have shown that the work of a civil engineer is far from just drawing on an orderly pursuit of knowledge supplied by the scientist. The civil engineer must after all be something of a scientist himself with an intimate acquaintance with not only one but several different fields. He must in addition be a first-hand observer of nature and a realist. If he is wrong he has not merely disproved a theory – he may have endangered life and property. This is in fact the challenge of civil engineering.

It now only remains for me once again to express my gratitude for the great honour I have received today, and to thank all of you for having followed me so patiently through one episode on our voyage through the life of a civil engineer.