MONTRÉAL 2000

Atelier Canadien sur la Géotechnique et les Risques Naturels : Bilan de la DIPCN

Réalisations et Perspectives

Comptes rendus

53e CONFÉRENCE CANADIENNE DE GÉOTECHNIQUE

LA GÉOTECHNIQUE À L'AUBE DU 3E MILLÉNAIRE

Canadian Workshop on Geotechnique and Natural Hazards: An IDNDR Perspective

Achievements and Prospects

Proceedings

53RD CANADIAN GEOTECHNICAL CONFERENCE

GEOTECHNICAL ENGINEERING AT THE DAWN OF THE 3RD MILLENNIUM

R.Couture & S.G. Evans
(Editors/Éditeurs)

CANADA 1842 GEOLOGICAL SURVEY - COMMISSION GÉOLOGIQUE

Emergency Preparedness Canada
Protection civile Canada

LA SOCIÉTÉ CANADIENNE DE GÉOTECHNIQUE
CANADA
THE CANADIAN GEOTECHNICAL SOCIETY

15-18 OCT 2000
DELTA CENTRE-VILLE
777, UNIVERSITY
MONTRÉAL (QUÉBEC)
CANADA

MONTRÉAL 2000

Comptes rendus de l'atelier canadien sur la géotechnique et les risques naturels : Bilan de la DIPCN

Proceedings of the Canadian Workshop on Geotechnique and Natural Hazards: An IDNDR Perspective

Montréal, Québec — Montreal, Quebec

18 octobre 2000 — October 18, 2000

Organisateurs / Convenors

Dr. Réjean Couture ing.
Commission géologique du Canada
601 rue Booth Ottawa (ON) K1A 0E8
Tél: 613-943-5237
Fax: 613-992-0190
Courriel : rcouture@nrcan.gc.ca

Dr. Stephen G. Evans
Geological Survey of Canada
601 Booth Street Ottawa (ON) K1A 0E8
Tel: 613-996-7648
Fax: 613-992-0190
Email: evans@nrcan.gc.ca

Adresses du site sur la Toile / Web site:

http://sts.gsc.nrcan.gc.ca/idndr
http://sts.gsc.nrcan.gc.ca/egd/ST-SCG.html

The Canadian Geotechnical Society — La Société canadienne de géotechnique

Collaborateurs

Société Canadienne de Géotechnique, Comité technique sur les glissements de terrain (SCG)

Commission géologique du Canada, Division des sciences du terrain (CGC)

Comité national canadien de la Décennie sur la réduction des désastres naturels (CNC-DIRDN)

Association internationale pour la géologie de l'ingénieur et de l'environnement (AIGI)

Comité technique sur les glissements de terrain de la Société internationale de mécanique des sols et de géotechnique (TC-11, SIMSG)

Protection civile du Canada (PCC)

Supporting organizations

Canadian Geotechnical Society, Landslide Technical Committee (CGS)

Geological Survey of Canada, Terrain Science Division (GSC)

Canadian National Committee of the International Decade for the Natural Disasters Reduction (CNC-IDNDR)

International Association for Engineering Geology and Environment (IAEG)

Technical Committee on Landslides of the International Society for Soil Mechanics and Geotechnical Engineering (TC-11, ISSMGE)

Emergency Preparedness Canada (EPC)

Emergency Preparedness Canada | Protection civile Canada

MONTRÉAL 2000

Atelier Canadien sur la Géotechnique et les Risques Naturels : Bilan de la DIPCN

Réalisations et Perspectives

Comptes rendus

53e Conférence Canadienne de Géotechnique

La géotechnique à l'aube du 3e millénaire

Canadian Workshop on Geotechnique and Natural Hazards: An IDNDR Perspective

Achievements and Prospects

Proceedings

53rd Canadian Geotechnical Conference

Geotechnical Engineering at the Dawn of the 3rd Millennium

R.Couture & S.G. Evans
(Editors/Éditeurs)

Emergency Preparedness Canada — Protection civile Canada

La Société canadienne de géotechnique — The Canadian Geotechnical Society

Imprimé et relié au Canada
Printed and bound in Canada

Édité par / Edited by : R.Couture & S.G. Evans

Imprimé par / Printed by :
Division de la géologie de l'ingénieur
(Société Canadienne de Géotechnique)
Engineering Geology Division
(Canadian Geotechnical Society)

ISBN 0-920505-17-1

Vendu par / Sold by :
Division de la géologie de l'ingénieur
(Société Canadienne de Géotechnique)
Engineering Geology Division
(Canadian Geotechnical Society)

Emergency Preparedness Canada
Protection civile Canada

Avant-propos

Dans le but de marquer la fin de la Décennie Internationale pour la Prévention des Catastrophes Naturels (DIPCN), la **Division géologie de l'ingénieur de la Société canadienne de géotechnique**, le groupe national canadien de l'**AIGI**, organise un **Atelier canadien sur la géotechnique et les risques naturels** avec l'appui du Comité national canadien de la **DIPCN**. De nombreux désastres naturels sont survenus à travers le Canada au cours du dernier siècle, dont plus récemment des avalanches de neiges (Colombie-Britannique, hiver 1999), des tempêtes de verglas (Basses-Terres du Saint-Laurent, hiver 1998), des inondations (Saguenay, été 1996; Bassin de la Rivière Rouge, printemps 1997) ainsi que des glissements de terrain affectant les artères de transport.

En décembre 1989, l'Assemblée générale des Nations Unies a déclaré la période 1990-2000 comme la **Décennie International pour la Prévention des Catastrophes Naturels (DIPCN)**. Cette décennie est destinée à promouvoir la coopération internationale afin de réduire les effets globaux des désastres naturels. Le Canada a la chance de compter sur un excellent réseau d'experts de renommée internationale, et d'excellents praticiens qui ont à cœur l'étude des risques naturels. Or, cet atelier réunira les experts canadiens dans le but d'examiner et de synthétiser les actions canadiennes liées à la réduction des risques naturels, de faire le point sur les axes de recherche futurs ainsi que de mettre de l'avant des lignes de conduite appropriées et des stratégies pour la réduction des impacts des risques naturels, tel que les glissements de terrain, les séismes, les inondations, et les avalanches de neige. Douze conférenciers invités présenteront leurs idées sur les aspects géotechniques des désastres naturels. L'Atelier est organisé en collaboration avec la **Commission géologique du Canada** et la **Protection civile du Canada** sous les auspices du Comité technique **TC11 de l'ISSMGE**.

Preface

To mark the closing of the International Decade for Natural Disaster Reduction (IDNDR), the **Engineering Geology Division of the Canadian Geotechnical Society**, the Canadian National Group of **IAEG**, has organized a **Canadian Workshop on Geotechnique and Natural Disasters** sponsored by the Canadian National Committee of the IDNDR. Natural disasters have occurred across Canada in the last century, recent examples being events related to snow avalanche (British Columbia, winter 1999), ice storm (St.Laurent lowlands, winter 1998), floods (Red River Basin, spring 1997; Saguenay River, July 1996) and landslides (several incidents related to lifeline integrity); these events resulted in significant life loss and affected several millions of Canadians.

In December 1989, The **International Decade for Natural Disaster Reduction (IDNDR)** was declared by the United Nations General Assembly. Canada, as a developed country, is fortunate to have a good network of well renowned experts and excellent practioners with interests in geotechnique and natural hazards. This workshop will bring together Canadian experts to examine and synthesize Canadian achievements related to natural hazard reduction, to take stock of future research, and to devise appropriate guidelines and strategies to reduce future impacts of natural disasters, such as landslides, earthquakes, floods, and snow avalanches. Twelve invited speakers will present their view on geotechnical aspects of natural hazards. The Workshop is organized in association with the **Geological Survey of Canada** and **Emergency Preparedness Canada** and under the auspices of the Technical Committee **TC11 of the ISSMGE**.

Table des matières / Table of contents

MONTRÉAL
2000

Atelier Canadien sur la Géotechnique et les Risques Naturels : Bilan de la DIPCN

Réalisations et Perspectives

53e Conférence Canadienne de Géotechnique

La géotechnique à l'aube du 3e millénaire

Canadian Workshop on Geotechnique and Natural Hazards: An IDNDR Perspective

Achievements and Prospects

53rd Canadian Geotechnical Conference

Geotechnical Engineering at the Dawn of the 3rd Millennium

Comptes rendus Proceedings

The Canadian Geotechnical Society
La Société canadienne de Géotechnique

Catastrophic Channel Widening During Extreme Floods – Examples from the 1996 Flooding in the Saguenay Valley

Gregory R. Brooks
Geological Survey of Canada, 601 Booth Street, Ottawa, ON, K1A 0E8
Email: *greg.brooks@nrcan.gc.ca*

Introduction

Between July 19 and 21, 1996, flooding triggered by a severe rainstorm caused widespread damage along the north shore of the St. Lawrence River between Trois-Rivières and Sept-Îles, and within the Saguenay Valley, Quebec. The heaviest zone of rainfall accumulation occurred in a section of the Laurentian Highlands located just south of the Jonquière-Chicoutimi-La Baie area of the Saguenay Valley, where up to 279 mm of rain fell within a 36 hour period (CSTGB, 1997). The worst flooding occurred along the lower reaches of north-flowing tributaries of the Saguenay River that drained the zone where in excess of 200 mm rain fell.

Among the many impacts, the flooding caused catastrophic channel erosion along sections of the Ha! Ha! and à Mars rivers in the La Baie area (Fig. 1). Along the Ha! Ha! River, the flooding was greatly accentuated by the breaching of a dike that caused the rapid draining of a reservoir, while along the à Mars River, the flooding was exclusively from rainstorm runoff. The geomorphic impacts along both rivers provide excellent case studies of large-scale channel erosion, which can be a significant hazard of flooding in some geomorphic settings.

Ha! Ha! River

The flood along the Ha! Ha! River was linked closely to events at the Ha! Ha! Lake reservoir, as documented by CSTGB (1997), INRS-Eau (1997), Lapointe et al. (1998) and Brooks and Lawrence (1999). During the storm, rainfall runoff into the lake exceeded the available spilling capacity of the control dam causing the reservoir level to rise. The reservoir eventually rose and overtopped the Cut-away dike located about 1.5 km south of the control structure (Fig. 1). The overtopping water breached the earthen dike (2-3 m high, 162 m wide) and incised up to 14 m into primarily till, causing the reservoir to drain rapidly over a period of 18 hr. The escaping reservoir water greatly accentuated flooding downstream, which was already in progress from the rainstorm runoff. Estimates of the peak discharge of the resulting combined flood range from 910 to 1380 m^3s^{-1} at the mouth of the breach, and from 1080 to 1260 m^3s^{-1} near the river mouth (see CSTGB, 1997; INRS-Eau, 1997; Lapointe et al., 1998; Brooks and Lawrence, 1999). By comparison, the peak discharge near the river mouth would have been an estimated 384 m^3s^{-1}, exclusively from rainstorm runoff, approximately a third of the actual flood discharge (CSTGB, 1997; INRS-Eau, 1997). Based on the pre-flood discharge record, the 100-yr flood is estimated to be 130 m^3s^{-1}, which is substantially smaller than the flood (Lapointe et al., 1998).

The flooding downstream of the Cut-away dike had severe, but variable, geomorphic impacts over the 35.5 km river distance to the river mouth. The river is divided in seven reaches (numbered sequentially downstream) based on whether erosion or deposition was the dominant process and on the degree of widening. These reaches and the pre- and post-flood channel widths are summarized diagrammatically in Fig. 2. The descriptions that follow are derived from data contained in Brooks and Lawrence (1999) and INRS-Eau (1997). The river distances mentioned in the text refer to kilometre distance upstream from the river mouth (Fig. 1).

Of the seven reaches, five reaches, representing about 70% of the study reach, were dominated by erosion (Fig. 2). Reach 1 represents a completely new channel (60 to 144 m wide, mean 98 m) that drained Lake Ha! Ha! from the breached dike to the pre-flood channel course 2 km downstream. Separate sections experiencing erosion are distinguished in reach 3 (km 27.5 to 16) and reach 4 (km 16 to 12.5). Reach 3 experienced comparatively moderate channel widening (post-flood channel, 22 to 111 m wide, mean 54 m, versus pre-flood channel, 10 to 54 m wide, mean 24 m; Fig 2), which was generally limited by the confined morphology of the valley bottom. Nevertheless, the pre-flood channel was completely changed by the flood flow. Along reach 4, the river course was profoundly altered. At about km 13, floodwaters overtopped a low divide and flowed into a ravine that provided an alternate route down valley before rejoining the pre-flood course at km 12.5. Subsequently, deep incision and extensive lateral erosion into unconsolidated deposits along the ravine ensued and propagated upstream along the river course from km 13 to about km 16. The depth of incision decreased upstream gradually from a maximum of about 20 m at km 13 to several m at km 16. The post-flood channel was 72 to 190 m wide (mean 136 m) compared to the 12 to 40 m wide (mean 24 m) pre-flood channel (Fig. 2).

Along reach 6 (km 8 to 4.5), the river channel was widened and deepened, stripping the pre-flood alluvium from the valley floor. The post-flood channel was 34 to 88 m wide (mean 68 m) compared to the pre-flood channel, 8 to 34 m wide (mean 24 m). As was the case along reach 3, the widening was restricted by the narrow morphology of the valley bottom, but also by resistant glacial and glacio-marine deposits, and, locally, by exposed bedrock. Along a canyon (km 5 to 4.5), the bedrock was extensively scoured of vegetation and small, thin pockets of overburden by the flood waters.

Initially along reach 7 between km 4.5 and 3.25, the channel was extensively widened, destroying the pre-flood channel; alluvium was removed completely, and the post-flood river flowed on exposed marine sediments. The width of the post-flood channel ranged from 62 to 145 m (mean 105 m) compared to a width of 24 to 32 m (mean 28 m) for the pre-flood channel (Fig. 2). Up to about 6 m of incision occurred locally. Below km 3.25, extensive widening of the channel occurred through lateral erosion of both the floodplain and low terraces along the valley bottom margin. The width of the post-flood channel ranged from 92 to 281 m (mean 160 m) compared to a width of 15 to 110 m (mean 47 m) for the pre-flood channel (Fig. 2). In places, the post-flood river morphology was multi-channeled and resembled a braided planform. Sediments derived from the river erosion upstream were deposited at the river mouth on the tidal flats in Ha! Ha! Bay.

Deposition was the dominant geomorphic effect along reach 2 (km 33.5 to 27.5) and reach 5 (km 12.5 and 8). Along reach 2, there was negligible to minor erosion of the pre-flood channel, while along reach 5, the pre-flood channel was buried beneath an extensive sheet of alluvium (up to 6 m thick).

River à Mars

Along the à Mars River, the peak discharge at the river mouth during the flood is estimated to be 445 m^3s^{-1}, based on hydrologic modeling of the storm runoff (CSTGB, 1997). Since the river is not gauged, there are no pre-flood discharge data to compare to this flow.

This summary of the geomorphic impacts of the flood relates exclusively to the lower 10 km of the river since immediately upstream the river flows within bedrock and the channel was not significantly modified. As was the case with the Ha! Ha! River, the geomorphic impacts are depicted diagrammatically in terms of the pre- and post-flood channel width (Fig. 3). With the à Mars River, there is no subdivision because the entire study reach experienced large-scale erosion. Of note, the valley gradient along the study reach is a uniform 0.012.

During the flood, catastrophic lateral bank erosion and reworking of the floodplain occurred to the pre-flood meandering channel along the entire 10 km study reach. This caused substantial widening of the river channel (locally up to 400 m), especially between km 9 to 8 and km 7 to 4 (Fig. 3). The greatest widening was along sections where the pre-flood channel was more sinuous and the floodplain widest. Along the other sections, the floodplain was more confined by alluvial terraces. There was no widening below km 0.5 because the banks were armoured by rip-rap.

In conjunction with the channel widening, a large proportion of the floodplain was reworked destroying the meandering planform of the pre-flood river, and allowing the river to take a more direct route down the valley. This occurred through a combination of concave bank erosion, lateral bank erosion, channel avulsions and the re-activation of abandoned and inactive channels. Terrace and valley side erosion occurred where the flood flow became directed against the margins of the valley bottom. Notably, the post-flood river was divided into multiple channels and thus transformed from a meandering to braided channel planform.

Discussion

Along the Ha! Ha! River, large-scale erosion in the form of channel widening and, in places, incision, occurred along the reaches 1, 3, 4, 6, and 7 (Fig 2), where the pre-flood channel morphology was destroyed. Along these reaches, the energy of the flood flow obviously exceeded the erosive threshold of the pre-flood channel perimeter and valley bottom. The enormous and exceptional discharge of the combined dike breach–rainstorm runoff flood was a major factor in the surpassing of this erosive threshold along the 25 km distance represented by these five reaches.

For the purpose of assessing the erosive threshold, of particular interest are reaches 2 and 5 (km 33.5 to 27.5 and km 16 to 12.5, respectively) which experienced deposition rather than erosion during the flood. The flow energy along these reaches obviously was below the erosive threshold. Expressed as unit stream power (ω), following Baker and Costa (1987), flow energy can be defined quantitatively as:

$$\omega = \gamma QS/w \qquad (1)$$

where, 'ω' is unit stream power (Wm^{-2}), 'γ' is specific weight of water (assumed to be 9800 Nm^{-3}, the value for clear water), 'Q' is discharge (m^3s^{-1}), 'S' is energy slope (assumed to be reasonably similar to the pre-flood valley slope), and 'w' is width of the flood flow (m).

Since both discharge and flood width are similar in magnitude to those along the five reaches that experienced erosion (Brooks and Lawrence, 1999), the factor limiting flow energy along the two depositional reaches is valley gradient. Not surprisingly, the valley gradient along reaches 2 and 5 are 0.016 and 0.002, respectively, the lowest along the river, in some cases, lower by two orders-of-magnitude. Estimates of unit stream power for the two reaches are 59 to 289 Nm^{-2} (reach 2) and 64 to 260 Nm^{-2} (reach 5); the range reflecting variation in the flood width along the reaches and estimates of flood discharge (Brooks and Lawrence, 1999). These values are below the threshold of 300 Wm^{-2} that has been identified elsewhere as the approximate upper limit of the erosive threshold (see Miller, 1990; Magilligan, 1992; Lapointe et al., 1998). The erosive threshold along the Ha! Ha! River study reaches is a function of, for example, the local valley bottom roughness, vegetative cover, and surficial material.

The catastrophic erosion along the à Mars River study reach indicates that the flow energy of the flood was above erosive threshold of the valley bottom. That the flood flow exceeded this threshold is noteworthy because the à Mars River flood was the product entirely of the 'natural' hydrological regime. This occurrence suggests that the large-scale erosion of the valley bottom and the associated transformation of the channel planform from meandering to braided, may well have occurred during previous extreme floods. Such planform transformations commonly are attributed to river morphologies that are transitional between meandering and braided. Brooks and Lawrence (submitted) argue that the lower à Mars River is a transitional meandering-braided planform based on the presence locally of characteristic channel features (e.g., short sections of split- or multiple-channels, small side channels, partially vegetated chute channels), as well as empirical slope-discharge plots that show that the à Mars channel falls on or near the lower boundary of the braided planform field. Given a sufficient period of time prior to the next severe flood, it would be expected that vegetation would become established on the subaerial portions of the broad post-flood channel and that the river channel would revert gradually to a single-channeled, meandering planform. However, as part of the post-flood reconstruction in the area, there has been substantial artificial filling along the flood channel and training of the river course to accelerate this process (see Ministère du Conseil exécutif Québec, 1997).

Concluding Remarks

Over the past decade or so, it has become increasingly recognized that some river planforms are vulnerable to catastrophic erosion during extreme floods. This has major repercussions for communities and infrastructure located proximal to rivers. Along both the Ha! Ha! and à Mars rivers, buildings, roads, and railway lines constructed on surfaces above the level of flooding were lost or damaged due to undermining from lateral bank erosion. Lateral erosion during a flood thus can represent a major hazard of flooding in addition to the obvious hazard of inundation.

In the case of the Ha! Ha! River, the length of river that experienced erosion reflects the enormous discharge of the combined dike breach–rainstorm runoff flood, in combination with the pre-flood valley gradient and width of the valley bottom. Except for the recurrence of another dike (or dam) breach, a flood of this magnitude would not be expected to occur through a strictly hydrometeorological mechanism. With the à Mars River, the erosion reflects the presence of a transitional pre-flood river planform that was vulnerable to catastrophic widening and a planform transformation during an extreme flood. It is very likely that the river has experienced a similar response to extreme floods in the past and, given a sufficient period of channel recovery, it must be anticipated that the à Mars River could again experience this during a future extreme flood. In Canada, rivers that periodically experience catastrophic widening causing planform transformations commonly are associated with high-energy mountain rivers in western Canada, but the case of the à Mars River clearly demonstrates that this type of planform exists on the Canadian Shield in eastern Canada as well.

References

Baker, V.R. and Costa, J.E., 1987. Flood power. *In*: L. Mayer and D. Nash (Editors), Catastrophic flooding; Allen and Unwin, London, p. 1-21.

Brooks G.R. and Lawrence, D.E., 1999. The drainage of Lac Ha! Ha! and downstream geomorphic impacts along the Ha! Ha! River, Saguenay area, Quebec, Canada; Geomorphology, v. 28, p. 141-168.

Brooks G.R. and Lawrence, D.E., submitted. Geomorphic effects of flooding along reaches of selected rivers in the Saguenay region, Quebec, July 1996; Géographie physique et Quaternaire.

Commission scientifique et technique sur la gestion des barrages (CSTGB), 1997. Rapport: Commission scientifique et technique sur la gestion des barrages; Quebec, Janvier 1997, 241 p. + annexes.

INRS-Eau, 1997. Simulation hydrodynamique et bilan sédimentaire des rivières Chicoutimi et des Ha! Ha! lors des crues exceptionnelles de juillet 1996; Rapport INRS-Eau No. R487, Travaux réalisés pour le compte de la Commission scientifique et technique sur la gestion des barrages, 207 p.

Lapointe, M. F., Secretan, Y., Driscoll, S. N., Bergeron, N., and Leclerc, M., 1998. Response of the Ha! Ha! River to the flood of July 1996 in the Saguenay Region of Quebec: large-scale avulsion in a glaciated valley; Water Resources Research, v. 34, p. 2383-2392.

Magilligan, F.J., 1992. Threshold and spatial variability of flood power during extreme floods; Geomorphology, v. 5, p. 373-390.

Miller, A.J., 1990. Flood hydrology and geomorphic effectiveness in the central Appalachians. Earth Surface Processes and Landforms; v. 15, p. 119-134.

Ministère du Conseil exécutif Québec, 1997. Les pluies diluviennes au Saguenay–Lac-Saint-Jean: Bilan un a après; Bureau de reconstruction et de relance de la région du Saguenay–Lac-Saint-Jean, Ministère du Conseil exécutif Québec, 67 p.

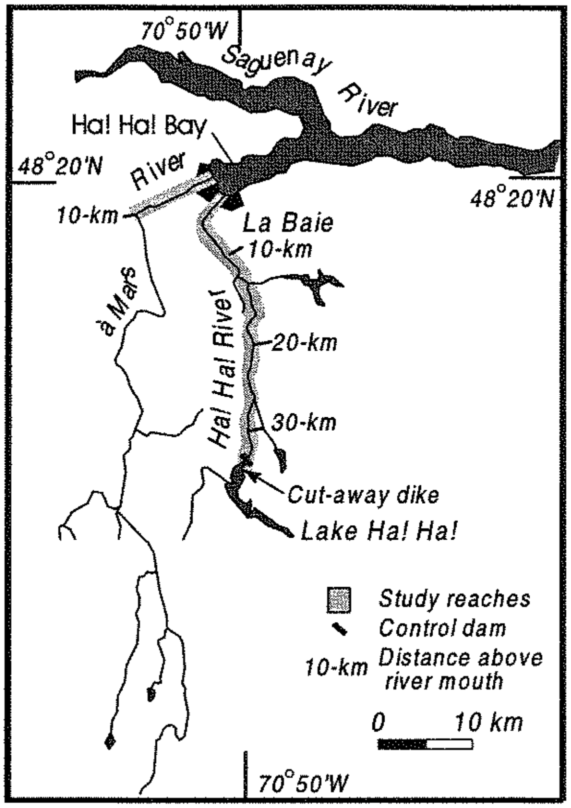


Figure 1. Map showing the study reaches along the Ha! Ha! and à Mars rivers in the Saguenay Valley, Quebec.

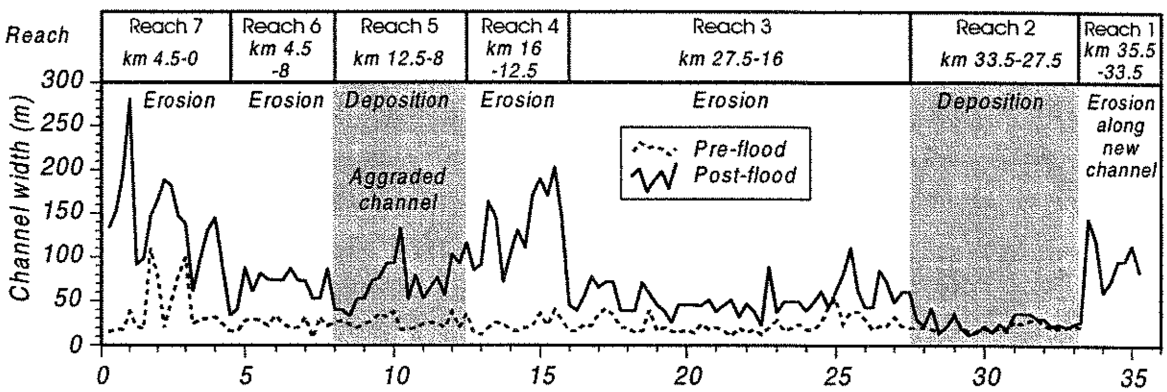


Figure 2. Categorization of geomorphic effects by reach and summary of channel widening along the Ha!Ha! River (after Brooks and Lawrence, 1999).

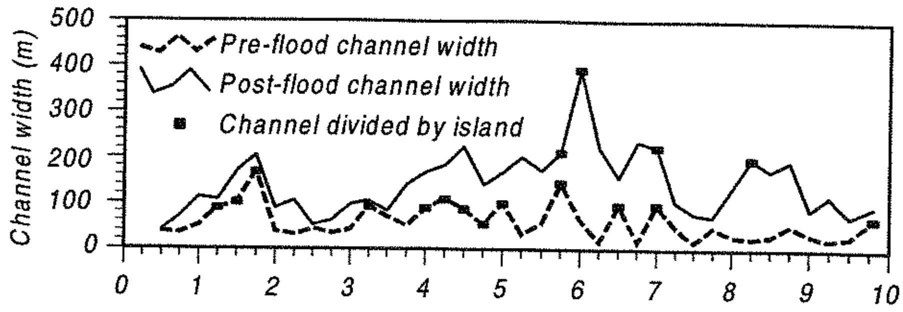


Figure 3. Summary of channel widening along the à Mars River study reach (after Brooks and Lawrence, submitted).

The Earthquake Threat in Southwestern British Columbia: A Geological Perspective

John J. Clague
Department of Earth Sciences, Simon Fraser University, Burnaby, B.C. V5A 1S6, and
Geological Survey of Canada, 101 – 605 Robson St., Vancouver, B.C. V6B 5J3
e-mail: *jclague@sfu.ca*

Western British Columbia is one of the most seismically active areas in Canada. Most earthquakes in the region occur offshore on spreading centres of the Juan de Fuca plate and on transform faults that mark plate boundaries. These earthquakes are far from populated areas of southwestern British Columbia and thus pose little threat to people living there. However, earthquakes are also common beneath Vancouver Island, the adjacent British Columbia mainland, the southern Strait of Georgia, and northwestern Washington state (Rogers, 1994). Nine moderate to large earthquakes (moment magnitude, M_w, 6-7.5) have struck this region in the last 130 years, most recently in 1965 at Seattle. This record indicates that the average return period for potentially destructive earthquakes in southwestern British Columbia and northwestern Washington is about 15 years, although the time between successive events during the historical period has varied considerably.

Three of the nine largest historical earthquakes in the region occurred at relatively shallow depth beneath central Vancouver Island in a zone parallel to and east of the fault delineating the northern end of the Juan de Fuca plate. Four of the nine occurred beneath the southern Puget Lowland between Seattle and Olympia, Washington. The historical record is too brief, however, to conclude that, in the future, most large earthquakes in the region will be located in these two areas.

Some of the historical earthquakes in southwestern British Columbia and northwestern Washington state occurred on faults within the crust of North America and are referred to as crustal earthquakes. Others had much deeper sources, in the Juan de Fuca plate, which is subducting beneath North America at the Cascadia subduction zone (subcrustal earthquakes) (Fig. 1). In contrast, the boundary between the Juan de Fuca and North America plates is aseismic. Because of this, some scientists have argued that the two plates are sliding continuously past one another with no significant accumulation of strain and, consequently, the Cascadia subduction zone is incapable of producing a large plate-boundary earthquake. Geophysical data obtained in recent years, however, demonstrate that part of the subduction zone is locked and that strain is accumulating in the overlying crust (Hyndman and Wang, 1993; Dragert *et al.*, 1994; Dragert and Hyndman, 1995). The buildup of strain is manifested at the surface by shortening and

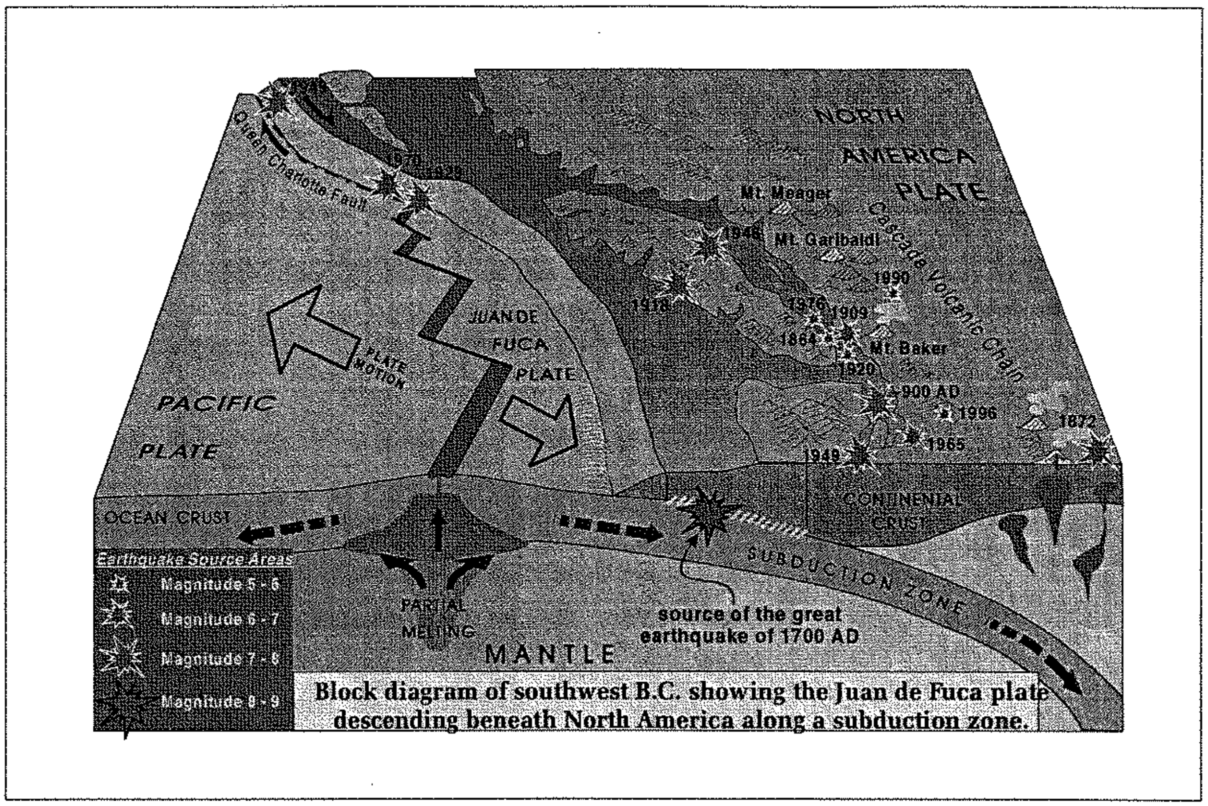


Figure 1. Plate tectonic setting of southwestern British Columbia and northern Washington, showing epicentres of large historical earthquakes in the region.

uplift of western Vancouver Island. An implication of these data is that much of the strain eventually will be released during one or more great (M_w 8-9) earthquakes at the plate boundary.

Holocene sediments and landforms record the effects of large earthquakes, allowing one to extend the historical record of seismicity thousands of years into the past. Although paleoseismic information commonly is limited and incomplete, it can provide insights into rare large earthquakes that have no precedent in the historical period. In this context, geological data from tidal marshes and low-elevation bogs and lakes on the Pacific coast of North America from Vancouver Island to northern California show that historically unprecedented, great plate-boundary earthquakes have struck this region. Sediments in tidal marshes near Tofino and Ucluelet on Vancouver Island, for example, record a large earthquake and tsunami 300 years ago (Clague and Bobrowsky, 1994, 1999). A buried peaty soil, similar to the present-day marsh soil, is sharply overlain by a sheet of sand and by intertidal mud. Foraminifera and vascular plant fossils show that the subsurface peaty soil was submerged suddenly and covered by sand. Submergence is attributed to coseismic subsidence, and the sand overlying the soil was deposited by the tsunami triggered by the earthquake. Similar stratigraphic sequences of the same age have been reported from numerous estuaries along the Pacific coasts of Washington, Oregon, and northern California, suggesting that hundreds of kilometres of the subduction zone ruptured during a great earthquake 300 years ago (Atwater *et al.*, 1995; Nelson *et al.*, 1995; Clague, 1997). Dendrochronological dating of trees killed and injured by the earthquake in southern Washington indicates that the earthquake occurred in the winter of 1699-1700 (Yamaguchi *et al.*, 1997). The earthquake has been precisely dated at January 26, 1700, from written records of its tsunami in Japan (Satake *et al.*, 1996).

Other similar buried soils, which record older great plate-boundary earthquakes, are present in tidal marshes in Washington and Oregon (Fig. 2; Atwater and Hemphill-Haley, 1997). Radiocarbon ages on plant fossils recovered from the soils indicate that the average recurrence interval for great Cascadia earthquakes is about 500 years. Geological evidence has been found for large earthquakes in the Vancouver-Victoria area *about 3500 and 1700*

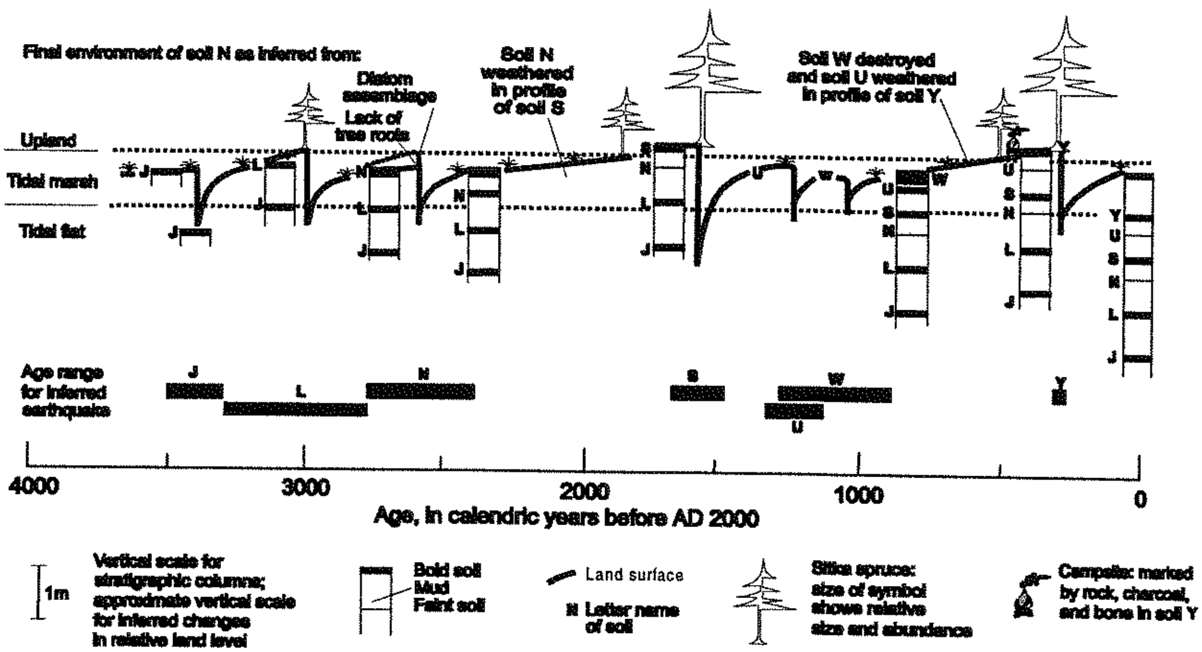


Figure 2. Diagrammatic representation of land level, vegetation, and soil changes at an estuary in southwestern Washington where there is evidence for seven large earthquakes in the last 4000 years (modified from Atwater and Hemphill-Haley, 1996, Fig. 15). Each buried soil, shown as a lettered horizontal line in the stratigraphic columns, records an earthquake that caused at least 0.5 m of subsidence. Soils are separated by silty and clayey sediments deposited between earthquakes. The age ranges of the earthquakes are based on radiocarbon ages.

radiocarbon years ago (Mathewes and Clague, 1992). The older event produced minor subsidence on southern Vancouver Island and perhaps uplift in the Vancouver area. The pattern of inferred deformation is consistent with that expected for a great plate-boundary earthquake. In contrast, the younger earthquake produced subsidence from Victoria to Vancouver and may have had a source in the North America plate rather than at the plate boundary. Silt and sand dykes and 'blows" (mounts of vented sediment) on the Fraser River delta near Vancouver are evidence of liquefaction during this earthquake (Clague *et al.*, 1997).

Geological evidence and historical earthquakes indicate that future seismic damage in southwestern British Columbia will result from fire, strong ground motions, tsunamis, landslides, liquefaction, and possibly subsidence and flooding of coastal areas (Clague, 1996). Intensity of ground shaking increases with magnitude and proximity to the focus, but is also strongly affected by local geology and topography and can vary by a factor of three or four over short distances. Ground motion commonly triggers secondary phenomena such as liquefaction, landslides, and fire, which may be responsible for much of the damage that occurs during an earthquake.

Seismic waves generated by Cascadia plate-boundary earthquakes attenuate over the 100-150 km they travel from their source to major cities on the south coast. Ground accelerations from these earthquakes at Vancouver and Victoria would not exceed those of a strong local earthquake. The strong motion of a great plate-boundary earthquake, however, would last much longer than that of a local quake. The energy spectrum of a great earthquake at epicentral distances of 100-150 km would be dominated by long-period, low amplitude waves, which are most damaging to large structures including some tall buildings, bridges, and tunnels. In contrast, the energy spectrum of a strong, local, shallow quake would have short-period, high amplitude waves, producing larger ground velocities and accelerations that would damage smaller structures.

Tsunamis triggered by earthquakes at subduction zones bordering the North Pacific Ocean are a hazard to some coastal communities in British Columbia (Clague, 1999). Communities on western Vancouver Island are most vulnerable, especially to tsunamis produced by earthquakes at the Cascadia subduction zone, which would strike soon after the shaking stops. In contrast, the tsunami hazard in areas bordering the Strait of Georgia is relatively low: a Cascadia tsunami would attenuate to 1 m or less before reaching Vancouver, and any waves generated by a strong crustal earthquake centered in the Strait of Georgia probably would be no more than 2 m high.

Water-saturated noncohesive sediment may liquefy when strongly shaken. Overlying cohesive sediment may move laterally on the liquefied layer towards a free face such as a river channel or bluff. Buildings, roads, and buried water, gas, and sewer lines commonly are damaged by these movements. The ground may also settle irregularly, further damaging structures. In southwestern British Columbia, liquefaction is most likely to occur in areas of water-saturated postglacial sediments underlying floodplains, deltas, and shorelines, and in areas underlain by uncompacted fill. Most of these areas are at or near sea level. Higher ground underlain by Pleistocene sediments is much less susceptible to liquefaction, and liquefaction will not occur where bedrock is at or very near the surface. Seismic microzonation mapping and geological studies have identified areas in and around Victoria and Vancouver that are susceptible to liquefaction. Buildings and other engineered structures in areas susceptible to seismic liquefaction must be designed to prevent damage due to irregular settling and fissuring of the ground above a liquefied layer.

Highways and rail lines that connect Vancouver to the rest of Canada follow steep-sided valleys. They could be blocked for days or even weeks by rockfalls and rockslides triggered by a strong earthquake. Landslides might also occur at the fronts of some deltas, such as the Squamish and Fraser River deltas, and along steep bluffs of Pleistocene sediments, such as are common around Vancouver. If an earthquake were to coincide with, or follow, a period of heavy rain, it might also trigger destructive debris flows.

The west coast of Vancouver Island could subside up to 2 m during a great earthquake at the Cascadia subduction zone, resulting in flooding of low-lying coastal areas. Coseismic uplift or subsidence might also occur within the epicentral area of a large crustal earthquake. For example, a large crustal quake about 1000 years ago produced up to 7 m of coseismic uplift adjacent to a fault that extends through Seattle (Bucknam *et al.*, 1992).

Analysis of the record of historical seismicity indicates that a M_w 6-7 earthquake is likely to occur somewhere in southwestern British Columbia or northwestern Washington state within the next 20 years, and is almost certain to happen within the next 50 years (Clague, 1996). If the short historical record is representative of seismicity over a much longer time frame, the next earthquake is most likely to be centered either on central Vancouver Island or in the southern Puget Lowland. Geological information indicates, however, that it could also occur elsewhere in the region, for example at or near Vancouver or Victoria.

Modified Mercalli Intensity plots of historical earthquakes in the region suggest that a future M_w 7 event would produce significant damage within 100 km of the epicentre; in contrast, the radius of widespread damage for a M_w 6 event would be about 50 km (Clague, 1996). Damage from a large crustal earthquake would result from ground motion, liquefaction, landslides, and fire. It is unlikely that such an earthquake would trigger a large tsunami, but there could be significant, localized, coseismic uplift or subsidence.

Subduction earthquakes are larger, but much rarer than potentially damaging earthquakes within the North America and Juan de Fuca plates. These exceptional earthquakes result from the rupture of segments of the Cascadia plate boundary that are many tens to hundreds of kilometres in length, and it is possible that the entire 1000 km length of the subduction zone could rupture during a single, cataclysmic M_w 9 event. This issue is critical in evaluating the threat posed by rare subduction earthquakes. A M_w 9 earthquake probably would damage all cities in western Oregon, western Washington, and southwestern British Columbia. A M_w 8 earthquake, on the other hand, would release approximately thirty times less energy and, as a result, would affect a much smaller area; one centered on the southernmost part of the Cascadia subduction zone, for example, might have little effect on Vancouver or Victoria.

The historical record and geological evidence suggest that large crustal and subcrustal are about fifty times more frequent than great subduction earthquakes in the Pacific Northwest (Clague, 1996). Consequently, it seems likely that the next damaging earthquake in the region will be a M_w 6-7 event location in the North America or Juan de Fuca plate. In view of the fact that a M_w 6.7 earthquake under Los Angeles in 1994 caused more than US $26 billion damage, we perhaps should concern ourselves more with M_w 6-7 earthquakes than with much rarer M_w 8-9 subduction events.

References

Atwater, B.F. and Hemphill-Haley, E. 1997. Recurrence intervals for great earthquakes of the past 3500 years at northeastern Willapa Bay, Washington. U.S. Geological Survey Professional Paper 1576.

Atwater, B.F., Nelson, A.R., Clague, J.J., Carver, G.A., Yamaguchi, D.K., Bobrowsky, P.T., Bourgeois, J., Darienzo, M.E., Grant, W.C., Hemphill-Haley, E., Kelsey, H.M., Jacoby, G.C., Nishenko, S.P, Palmer, S.P., Peterson, C.D., and Reinhart, M.A. 1995. Summary of coastal geologic evidence for past great earthquakes at the Cascadia subduction zone. *Earthquake Spectra, 11*: 1-18.

Bucknam, R.C., Hemphill-Haley, E., and Leopold, E.B. 1992. Abrupt uplift within the past 1700 years at southern Puget Sound, Washington. *Science, 258*: 1611-1614.

Clague, J.J. 1996. Paleoseismology and seismic hazards, southwestern British Columbia. Geological Survey of Canada, Bulletin 494.

Clague, J.J. 1997. Evidence for large earthquakes at the Cascadia subduction zone. *Reviews of Geophysics, 35:* 439-460.

Clague, J.J. 1999. Tsunami threat on the west coast. *Backscatter, 10(4)*: 10-13.

Clague, J.J. and Bobrowsky, P.T. 1994. Evidence for a large earthquake and tsunami 100-400 years ago on western Vancouver Island, British Columbia. *Quaternary Research, 41*: 176-184.

Clague, J.J. and Bobrowsky, P.T. 1999. The geological signature of great earthquakes off Canada's west coast. *Geoscience Canada, 26*: 1-15.

Clague, J.J., Naesgaard, E., and Nelson, A.R. 1997. Age and significance of earthquake-induced liquefaction near Vancouver, British Columbia, Canada. *Canadian Geotechnical Journal, 34*: 53-62.

Dragert, H. and Hyndman, R.D. 1995. Continuous GPS monitoring of elastic strain in the northern Cascadia subduction zone. *Geophysical Research Letters, 22*: 755-758.

Dragert, H., Hyndman, R.D., Rogers, G.C., and Wang, K. 1994. Current deformation and the width of the seismogenic zone of the northern Cascadia subduction thrust. *Journal of Geophysical Research, 99*: 653-688.

Hyndman, R.D. and Wang, K. 1993. Tectonic constraints on the zone of major thrust earthquake failure: the Cascadia subduction zone. *Journal of Geophysical Research, 98*: 2039-2060.

Mathewes, R.W. and Clague, J.J. 1992. Detection of large prehistoric earthquakes in the Pacific Northwest by microfossil analysis. *Science, 264*, 688-691.

Nelson, A.R., Atwater, B.F., Bobrowsky, P.T., Bradley, L.-A., Clague, J.J., Carver, G.A., Darienzo, M.E., Grant, W.C., Krueger, H.W., Sparks, R., Stafford, T.W., Jr., and Stuiver, M. 1995. Radiocarbon evidence for extensive plate-boundary rupture about 300 years ago at the Cascadia subduction zone. *Nature, 378*: 371-374.

Rogers, G.C. 1994. Earthquakes in the Vancouver area. *In* Monger, J.W.H. (ed.), Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia. Geological Survey of Canada, Bulletin 481, p. 221-229.

Satake, K., Shimazaki, K., Tsuji, Y., and Ueda, K. 1996. Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami records of January 1700. *Nature, 378*: 246-249.

Yamaguchi, D.K., Atwater, B.F., Bunker, D.E., Benson, B.E., and Reid, M.S. 1997. Tree-ring dating the 1700 Cascadia earthquake. *Nature, 389*: 922.

The Record of Disastrous Landslides and Geotechnical Failures in Canada 1840-1999: Implications for Risk Management

Stephen G. Evans
Geological Survey of Canada
601 Booth St. Ottawa (ON) K1A 0E8
Email: evans@nrcan.gc.ca

Introduction

Historical records of natural disasters are important in understanding disastrous processes (mechanics and causes), historical frequency and magnitude, and in pointing to ways in which they may be avoided or mitigated in future. They are also of considerable use in developing landslide risk criteria and can be used as reference levels in landslide risk assessment.

As part of the Canadian contribution to the IDNDR a verified data base of disastrous landslides and geotechnical failures in the historical period has been assembled (Evans, 1997; 1999; Evans et al., 1997). The project is now considered to be complete. This paper presents additional data and a revised analysis as well as exploring the contribution of technological landslide risk to landslide risk in Canada.

Events of concern in the present context are landslides in natural slopes or failures of artificial slopes, either built or excavated. The latter group of events are termed geotechnical failures. Evans (1997) defined a disastrous event in the Canadian context, as a single event failure which resulted, directly or indirectly, in the deaths of 3 or more people.

The historical period and the historical landslide record

Evans (1997, 1999) identified the two areas of Canada that are particularly vulnerable to damaging landslides and which have experienced the vast majority (91%) of the Nation's disastrous landslides and geotechnical failures. To obtain some idea of the length of population exposure to landslide hazard, it is of interest to define the historical period. In addition, the nature of the historical landslide record for the two regions is examined, recognizing that landslides must have affected aboriginal peoples (Evans, 1997) in the pre-European period.

St. Lawrence Lowlands

European settlements were not established in eastern Canada until the first decade of the seventeenth century culminating in the founding of Quebec by Champlain in 1608. The first European missionary arrived in New France in 1615 and the first settler in 1617 (Careless, 1970).

The first reported landslides are those in Leda Clay associated with the great earthquake (M ~ 7.0) which struck New France on February 5, 1663. Although the region was sparsely populated, the direct effects of the earthquake are recorded in correspondence by religious orders active in the area at the time. Indirect evidence of the earthquake's effects have been obtained by the radiocarbon dating of landslide debris (LaSalle and Chagnon, 1968; Leggett and LaSalle, 1978; Desjardins, 1980; Quilliam and Allard, 1989; Filion et al. 1991), dendrochronology (Filion et al. 1991), and the analysis of sediments in lakes and fiords (summarised in Syvitski and Schafer, 1996). It is evident that widespread landsliding took place throughout New France. We have not uncovered further reference to major landslides in the St. Lawrence Lowlands until 1771, the date of the earliest documented landslide at St-Pierre-de-la-Rivière-du-Sud, Quebec, in 1771. The landslide is described in *The Annual Register* (p. 164) for the year 1771 (Anonymous, 1779) and was a rapid retrogressive Leda Clay earthflow. One person was killed in the landslide when a farmhouse was buried in the debris.

Although the historical period is ca. 384 years, systematic landslide data exists only after 1840 (Evans, 1997), a record of 161 years.

Cordillera of western Canada

In western Canada the length of the historical period is considerably shorter. Alexander Mackenzie reached the Pacific at Bella Coola on July 22, 1793 only a month before Captain George Vancouver arrived on the coast by sea (Careless, 1970). This historic date gives the length of the historical period to 2000 of only 208 years. The first observations of a catastrophic landslide in the Cordillera are those made in 1858 describing the aftermath of the Rubble Creek landslide, southwest British Columbia, which occurred in the winter of 1855-56 (Hardy et al., 1978; Moore and Matthews, 1978). This timeline broadly corresponds to the beginning of scientific exploration in the Cordillera, began by The Palliser Expedition in 1857. The Cariboo gold rush of 1858 opened up the Interior of British Columbia, leading to the first newspaper report of a damaging landslide in the Cordillera at Barkerville, the centre of the Cariboo Gold Rush, in May 1866. This date marks the beginning of the systematic landslide record in the Cordillera giving a length of record to 2000 of only 135 years.

Thus despite differences in the historical period, the length of the systematic landslide record in both regions is comparable. The sources of landslide disaster data are outlined by Evans (1997, 1999).

Landslides and Geotechnical Failures; the historical record

A total of 43 events that met the nominal national disaster criterion defined above, occurred in Canada in a period of 160 years between 1840 and 1999 (Table 1). This is equivalent to a landslide disaster frequency of one every 3.7 years, or an annual frequency of 0.27. These disasters resulted in a minimum of 570 deaths.

Assessment of historical record

Landslide type

A re-examination of the 1915 Jane Camp disaster (Evans, 2000) and the addition of a further three landslide disaster events, has led to an assessment of destructive landslide types somewhat different to the first approximation suggested by Evans (1997). Based on Table 1 the most destructive were small-scale rockslides and rockfalls involving volumes of less than 100,000 m^3. These caused 27 % (155) of the deaths in seven events across Canada. Second, in terms of destructiveness were landslides in Leda Clay which caused 17.0% (98) of the deaths in 9 events in the St. Lawrence Lowlands of Quebec. The third most destructive type were geotechnical failures involving the failure of man-made slopes, which accounted for 84 deaths, 15 % of the total. The fourth most destructive landslide type consists of rock avalanches involving volumes in excess of 10 $x10^6$ m^3. Rock avalanches caused 15 % (83) of the total deaths in only 3 disaster events in the Cordillera. Fifth, were debris flows and debris avalanches involving volumes of 60,000 m^3 or less. These landslides caused 11% (65) of the disaster deaths in 13 events.

125 deaths (22 % of the total) were caused by rapid flowslide-type movements in Quaternary sediments (glaciolacustrine and glaciomarine) in 12 events in British Columbia and Quebec.

It is noted that there is no simple correlation between deaths per event and event magnitude, nor is the record dominated by large magnitude events usually associated with landslide disasters. Indeed, the data suggests that the greatest number of landslide deaths have been caused by small magnitude-high frequency landslides.

Secondary effects

Many of the landslide deaths were caused by the secondary effects of landslides and related geotechnical failure, i.e., landslide-generated displacement waves and outburst floods. These caused 147 (26%) of the total number of deaths in only 5 events.

The role of human forcing - technological landslide risk

Landslide disasters by their very nature occur in the vicinity of human activity which frequently has altered the natural condition of the failed slope. Changes in slope condition due to deforestation, irrigation, excavation in the surface or subsurface, are common. Fills or embankments may impart loading to slopes and block surface or subsurface drainage. Blasting may result in the dynamic loading of slopes. Thus, a listing of historical landslide disasters contains events which are partly, or largely, due to some element of human forcing and may thus be considered technological disasters. In the Canadian record 130 of the deaths (23%) are related to landslides caused directly or indirectly by human activity. These include deaths due to embankment failures, a landslide in an open pit mine that penetrated underground workings, and two deadly Leda Clay landslides caused by blasting. If the problematical 1903 Frank Slide, which may have been triggered by the effects of coal mining at the base of Turtle Mountain (Benko and Stead, 1998), and other landslides in which human activity was an important causal factor are included, this total becomes 261 or 46% of the total deaths.

If landslide disasters found to be the result of human negligence (Evans, 1997) it could be argued that over 50% of the landslide deaths in the record are due directly and indirectly to human activity.

A historical landslide disaster listing is therefore a composite record of events due to human and natural causes in varying proportions. Its use in the construction of F/N curves (Evans, 1997) must recognise that human activity has interacted with natural systems in complex ways generating hybrid events which blur the distinction between natural and man-made disasters. This is the case even though the failure of an artificial or modified natural slope system may be in response to an external natural trigger, most frequently an extreme meteorological event. A further point is that human activity not only increases risk by amplifying frequency but also increases risk by increasing vulnerability.

In the Canadian case, the natural landslide magnitude and frequency signal is significantly distorted by human forcing over a wide range of landslide magnitudes. Part of this distortion consists of an amplification of frequency resulting in increased landslide risk. In Table 1 a rough partition has been made between natural landslides and those involving artificial slopes, built slopes, or landslides in natural slopes triggered by human activity. These data have been used to define, as a first approximation, the contribution of technological landslide risk to the Canada landslide risk envelope (Fig. 1). A significant increase in risk is seen above the risk defined by the natural envelope across the magnitude range of landslide disasters (Fig. 1).

Conclusions

Approximately 570 people died in disastrous landslides and geotechnical failures in the period 1840 to 2000. British Columbia and Quebec sustained most damage. The most destructive landslide type in terms of total number of deaths in that time are small frequent landslides as opposed to large infrequent events. Even so Canada's largest single landslide disaster is the huge rock avalanche that buried part of the town of Frank in 1903. The Canada landslide risk envelope is largely defined by disastrous events that occurred before 1930 in what was essentially an unregulated pre-technical environment in a period of intense resource development. 432 (75% of the total) of the total fatalities in the Canadian landslide record took place before 1930. There is a strong suggestion that a major portion of the deaths in the record resulted from landslides, which were strongly influenced by human activity, and geotechnical failures. In the Canadian context, many disastrous landslides represent a technological failure triggered by an extreme meteorological event. Their presence in the record represents an element of added risk in the national landslide risk envelope. F/N curves constructed using historical data are used to define "acceptable" societal landslide risk; however, they contain significant elements of risk resulting from "unacceptable" technological failure. This is thought to be an important consideration in landslide risk management, identified as a key activity in the United Nations' International Strategy for Natural Disaster Reduction.

References

ANONYMOUS, 1779. The Annual Register, or a view of the history, politics and literature for the year 1771. 3rd Edition, London. Printed for J. Dodsley, Pall Mall.

BENKO, B. and STEAD, D. 1998. The Frank slide: a reexamination of the failure mechanism; Canadian Geotechnical Journal, v. 35, p. 399-311.

CARELESS, J.M.S. 1970. Canada:a story of challenge. Macmillan of Canada, 449 p.

DESJARDINS, R. 1980. Tremblements de terre et glissements de terrain: corrélation entre des datations au ^{14}C et des données historiques à Shawinigan, Quebec. Géographie physique et Quaternaire, 34 : 359-362.

EVANS, S.G. 1997. Fatal landslides and landslide risk in Canada. *In* Landslide Risk Assessment. *Edited by* D.M. Cruden and R. Fell A.A. Balkema, Rotterdam, pp. 185-196.

EVANS, S.G. 1999. Landslide Disasters in Canada 1840-1998. Geological Survey of Canada Open File 3712 (Map with marginal notes).

EVANS, S.G. 2000. The 1915 and 1921 disasters at the Britannia Mine complex, Howe Sound, British Columbia; geotechnical implications for intensive resource development in steep mountain watersheds in the Coast Mountains. Abstract 896 GeoCanada 2000 Conference CD.

EVANS, S.G., COUTURE, R., and CHAGNON, J-Y. 1997. Notes on major Leda Clay landslides, St. Lawrence Lowlands, eastern Canada 1615-1996. Proceedings, 50th Canadian Geotechnical Conference, Ottawa. Preprint Volume 2, pp. 839-846.

FILION, L., QUINTY,F., and BÉGIN,C. 1991. A chronology of landslide activity in the village of Riviere du Gouffre, Charlevoix, Quebec. Canadian Journal of Earth Sciences, 28: 250-256.

HARDY, R.M., MORGENSTERN, N.R., and PATTON, F.D. 1978:Report of the Garibaldi Advisory Panel; British Columbia Department of Highways, Victoria, British Columbia, 371 p.

INTERNATIONAL FEDERATION OF RED CROSS AND RED CRESCENT SOCIETIES, 1996. World Disasters Report 1995, 150 p.

LASALLE, P. and CHAGNON, J-Y. 1968. An ancient landslide along the Saguenay River, Quebec. Canadian Journal of Earth Sciences, 5: 548-549.

LEGGET, R.F. and LASALLE, P. 1978. Soil studies at Shipshaw, Quebec:1941 and 1969. Canadian Geotechnical Journal, 15 : 556-564.

MOORE, D.P. and MATHEWS, W.H. 1978: The Rubble Creek landslide, southwestern British Columbia; Canadian Journal of Earth Sciences, v. 15, p.1039-1052.

QUILLIAM, L. and ALLARD, M. 1989. Évolution géomorphologique du glissement de terrain et du marais littoral de Saint-Joseph-de-la-Rive, Charlevoix, Quebec. Géographie physique et Quaternaire, 43: 367-376.

SYVITSKI, J.P.M. and SCHAFER, C.T. 1996. Evidence for an earthquake-triggered basin collapse in Saguenay Fjord, Canada. Sedimentary Geology, 104: 127-153.

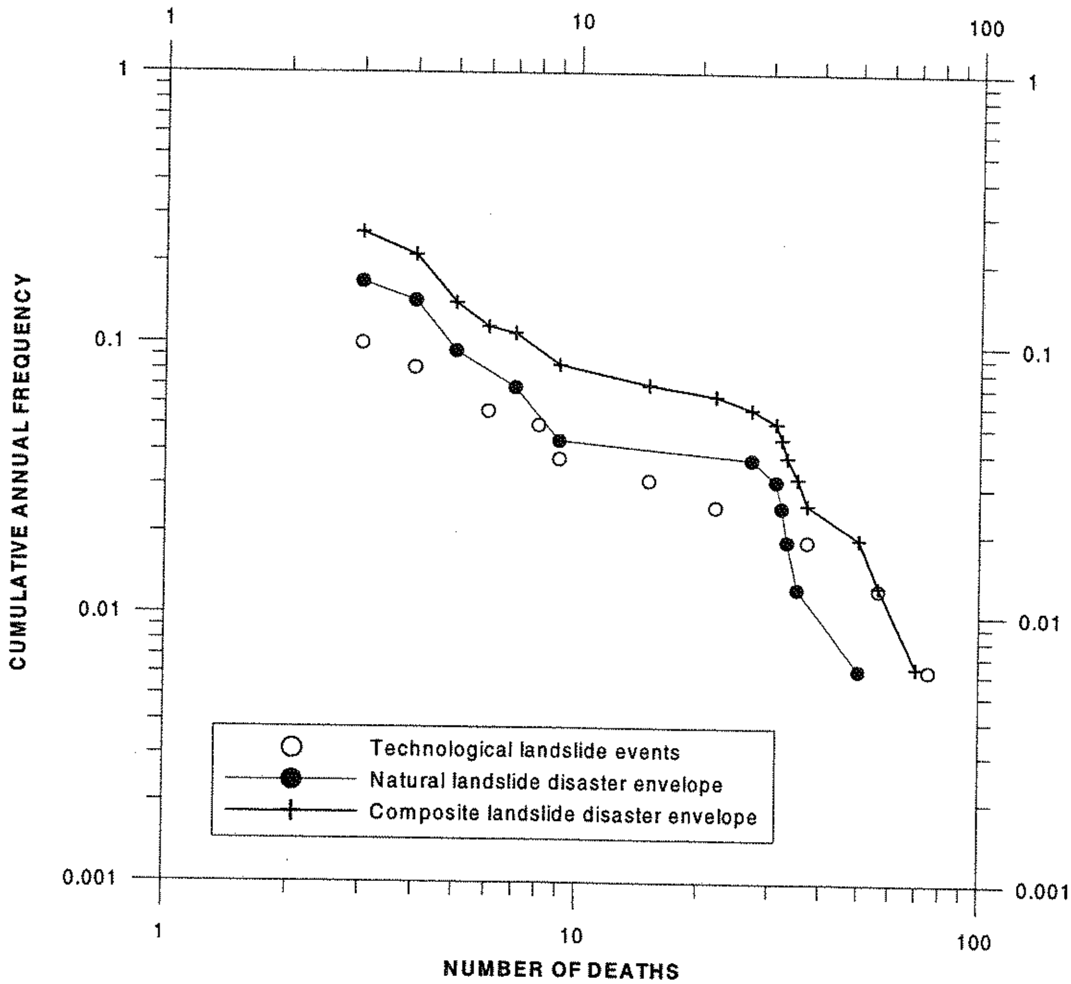


Fig. 1 *F/N curves constructed (see Evans (1997) for method) from data in Table 1 showing component of technological landslide risk in the composite national landslide disaster risk envelope.*

Table 1 Listing of disastrous landslides and geotechnical failures resulting in greater than 3 deaths for the period 1840-1999 (from Evans, 1999). Events are arranged in chronological order.

No.	Date	Location	Prov.	Deaths	Comments
1	1841/05/17	Quebec City	Que.	32	Rockslide destroyed houses on Champlain Street
2	1852/07/14	Quebec City	Que.	7	Rockslide destroyed houses on Champlain Street at Cap Blanc
3	1864/10/11	Quebec City	Que.	4	Rockslide destroyed houses on Champlain Street
4	1877/05/01	Ste-Genevieve-de-Batiscan	Que.	5	Earthflow in Leda Clay overwhelmed mill and adjoining house
5	1889/09/19	Quebec City	Que.	50	Rockslide destroyed houses on Champlain Street
6	1891/07/06	North Pacific Cannery	B.C.	35	Workers homes overwhelmed by debris flow or flood caused by breach of landslide dam after heavy rains
7	1894/04/27	St-Alban	Que.	4	Farmhouses carried away by massive landslide in Leda Clay
8	1895/09/21	St-Luc-de-Vincennes	Que.	5	Home destroyed by earthflow in Leda Clay
9	1897/04/20	Sheep Creek, near Rossland	B.C.	7	Debris flow struck railway maintenance camp
10	1898/02/??	Quesnel Forks	B.C.	3	Victims were miners
11	1903/04/23	Frank	Alta.	75	Rock avalanche buried part of the coal mining town of Frank
12	1905/08/13	Spences Bridge	B.C.	15	Landslide into Thompson River caused displacement wave which swept victims away
13	1908/04/26	Notre-Dame-de-la-Salette	Que.	33	Landslide in Leda Clay into Lievre River caused wave containing blocks of ice which destroyed homes
14	1909/11/28	Burnaby	B.C.	22	Slump of railway embankment; work train derailed
15	1910/04/15	St-Alphonse-de-Bagotville	Que	4	Construction camp buried by landslide in Leda Clay caused by blasting during construction of railway
16	1910/04/18	Coucoucache	Que	6	Slump of railway embankment; work train derailed
17	1915/03/22	Jane Camp	B.C.	56	Rock avalanche from above portal of mine swept into mining camp
18	1921/10/28	Britannia Beach	B.C.	37	Outburst flood caused by failure of railway fill swept away more than 50 houses 4.5 km downstream
19	1922/09/30	Elcho Harbour	B.C.	5	Debris avalanche caused by heavy rains destroyed logging camp
20	1929/11/18	Burin Peninsula	Nfl.	27	Tsunami generated by massive earthquake-generated submarine slump destroyed buildings along shore
21	1930/06/26	Capreol	Ont.	4	Slump of railway embankment; passenger train derailed into Vermillion River
22	1930/06/27	Crerar	Ont.	8	Slump of railway embankment; freight train derailed.
23	1938/09/01	St-Gregoire-de-Montmorency	Que.	4	Landslide caused by heavy rains destroyed apartment building below
24	1946/07/19	Beattie Mine, Duparquet	Que.	4	Landslide debris flowed into mine shaft killing miners underground
25	1955/11/12	Nicolet	Que.	3	Earthflow in Leda Clay : $10 M damage including destruction of church complex
26	1957/11/22	Prince Rupert	B.C.	7	Debris avalanche triggered by heavy rains buried 3 houses
27	1959/03/27	Revelstoke	B.C.	4	Landslide triggered by highway construction struck house
28	1960/09/07	McBride	B.C.	3	Debris flow ; victims were highway construction workers
29	1962/05/23	Riviere Toulnustouc	Que.	9	Workers killed by landslide in marine clay caused by blasting
30	1963/12/11	St-Joachim-de-Tourelle	Que.	4	Earthflow in Leda Clay; victims drove into landslide crater
31	1964/09/16	Ramsay Arm	B.C.	5	Debris flow caused by heavy rains struck logging camp
32	1965/01/09	Hope	B.C.	4	Massive rock avalanche buried vehicles on B.C. Highway #3
33	1965/01/14	Ocean Falls	B.C.	7	Slush avalanche/debris flow caused by melting snow struck community
34	1968/06/05	Camp Creek	B.C.	4	Debris flow caused by heavy rains struck car on Trans-Canada Highway
35	1969/02/09	Porteau	B.C.	3	Rockfall struck car at Porteau Bluffs on Squamish Highway
36	1971/05/04	St-Jean-Vianney	Que.	31	Rapid retrogressive flowslide in Leda Clay swept away 40 homes
37	1971/05/04	Boothroyd, Fraser Canyon	B.C.	3	CNR train derailed by rockfall.
38	1972/03/20	Michel	B.C.	3	Debris flow from coal mine waste dump struck CPR maintenance crew 16 km west of Crowsnest
39	1973/08/01	Harbour Breton	Nfl.	4	Debris avalanche struck houses. 4 houses swept into harbour and destroyed.
40	1975/07/22	Devastation Glacier	B.C.	4	Massive rock avalanche buries geophysical survey crew
41	1980/05/20	Belmoral Mine, Val D'Or	Que.	8	Cave-in of mine roof triggered a flow of lacustrine sediments into mine workings
42	1981/10/28	M-Creek Bridge, Highway 99	B.C.	9	4 vehicles plunged into creek after debris flow had destroyed bridge on Squamish Highway during heavy rains
43	1990/06/12	Joe Rich	B.C.	3	Debris avalanche caused by heavy rains destroyed house

A General Methodology for Landslide Hazard and Risk Assessment

Oldrich Hungr
Department of Earth and Ocean Sciences, University of British Columbia,
6339 Stores Road, Vancouver, B.C., V6T 1Z4, Canada
Email: ohungr@eos.ubc.ca

Introduction

Landslide hazard assessments are required for development in hilly or mountainous terrain. The scope of such work varies from brief site inspections to fairly extensive studies and involves substantial responsibility on the part of an engineering geologist.

Increased population leads to unprecedented demand for development land for housing, infrastructure and other facilities. At the same time, land availability is restricted by the growing need to protect natural areas and agricultural lands. As a result of these combined pressures, there is a tendency to develop marginal areas, such as those threatened by landslides. It is no longer sufficient to map hazard areas and exclude them from development. The society increasingly demands our profession to draw lines between acceptable and unacceptable hazards and risks.

Types of Landslide Hazards

Landslide terminology is covered by classification systems such as that of Varnes (1978) and Cruden and Varnes (1996). From the standpoint of hazard assessment, it is important to distinguish source area hazards, i.e. chances of damage to structures situated on top of a landslide and runout zone hazards, where damage results from landslide debris impacting a structure after travelling from a more or less distant source.

In the first case, the probability of damage equals the probability of landslide occurrence. The most common landslide type connected with such hazard is a slump or slide in cohesive soil or weak rock, often a re-activation of an earlier failure (Figure 1a). In the second case, the probability of damage equals the probability of occurrence, times the conditional probability that the landslide will reach the location of the structure. The most important landslide types exhibiting long runout are rock fall, rock slide, debris avalanche (Figure 1b), debris flow and flow slide. Earth flow associated with failure of clayey colluvium may also advance beyond its "normal" limit during surges.

Hazard and Risk Assessment and Acceptance

A general flow chart for hazard and risk assessment was suggested by Hungr (1997) and is reproduced in Table 1. The idea behind this chart is that risk assessment, i.e. the estimate of potential losses and their probability, forms a separate stage in the process. This stage requires input from parties other than the engineering geology specialist and also data regarding land use, structural engineering, social and economic issues. The earlier stage, "hazard assessment" consists of a detailed characterization of the potential hazards and their probability, requiring only geotechnical expertise.

Figure 1. a) House damaged as a result of being situated on a re-activated landslide, Kelso, WA. b)House damaged by a debris avalanche from an adjacent slope (White Rock, B.C.)

Acceptance can be queried at the end of either of the two stages. In the hazard assessment stage, we may ask: "Is it desirable to place persons or facilities in an area subject to a certain type of hazard, with a given intensity and probability of impact?" In the risk assessment stage, the question is: "Can we tolerate certain potential losses (including loss of life) with a given probability of occurrence?" In this writer's opinion, the answer to either question should be provided by the individual whose life or property are being put at risk, or by an authority which is legally responsible for the risk area, such as a government agency. The engineering geology professional's responsibility should be limited to supplying information concerning the nature of the hazard or the level of risk, including estimates of probability. The following examples illustrate some possible approaches towards this goal.

Hazard assessment, source areas

In case of source area hazards, usually the only information required is the extent of the potentially unstable area (often expressed as a "setback" from slope crest) and the probability of occurrence. Setbacks from valley crests are often derived empirically, by observing the geometry of natural landslides and long term stable slopes (e.g. Cruden et al., 1989). One notable attempt to incorporate material properties into an empirical setback estimate is the correlation of quick clay retrogression distance with the stability number by Mitchell and Markell (1974). However, mapping of sensitivity contours in leached marine clay deposits using field vane or CP tests is a more accurate method (K. Senneset, pers. comm.). A database of natural landslides can also be used to estimate the probability of occurrence.

Stage 1: Hazard assessment	
Step	*Action*
1.	Recognition of hazard (i.e. there is a possibility of landslides of certain types)
2.	Estimation of magnitudes (volumes)
3.	Estimation of the corresponding probabilities of occurrence
4.	Estimation of hazard intensity distribution
5.	Estimation of the probabilities related to intensity
6.	Hazard assesment report
Stage 2: Risk assessment	
Step	*Action*
7.	Determination of elements at risk
8.	Estimation of vulnerabilities
9.	Calculation of specific risks
10.	Calculation of the total risk.
11.	Assessment of risk acceptability
12.	Mitigation of risk (if necessary).

Table 1. Modified flow chart for a geotechnical hazard and risk assessment (Hungr, 1997).

A more definite estimate of setback distances can be obtained through detailed stability analysis of a given slope, although this requires an elaborate site investigation. It is also difficult to associate the results with probability of occurrence.

A method for empirical mapping of landslide susceptibility as a function of slope and geology was proposed by Brabb (1991), among others (cf. Resource Inventory Committee, 1996). An important element of such mapping is the recognition of active and dormant landslide terrain.

Hazard assessment, runout zone

Direct estimation of the extent of the runout zone is possible only for rock fall. The probable reach of large boulders rolling beyond the margins of talus deposits can be estimated by projecting an empirical "shadow angle" from the talus apex (Evans and Hungr, 1993).

Debris flows, having a defined path and deposition area, permit some specific approaches to runout zone mapping. In a preliminary analysis, fans recognized as being of colluvial origin can be assumed subject to debris flows in their entirety (Jackson et al., 1987). More refined mapping of debris flow hazards on fans requires that potential volumes (magnitudes) of debris flow events be estimated. Once the debris flow magnitude is set, an extent of the direct impact zone (deposition area of the coarse debris load) can be determined by assuming an average deposit thickness, or by conducting a dynamic runout analysis using an appropriate model.

Several debris flow mapping projects in BC used the concept of a "design event", i.e. the largest debris flow that could be expected within a given time period. Where used to outline areas of land restriction, the applicable time period should be at least 500 years, i.e. the design even should for practical purposes be the largest one could reasonably expect at the site. The estimate of the design event magnitude can be based on an inventory of debris available in channels feeding the fan (VanDine, 1985). Empirical formulas using the concept of "channel yield rates" in m^3 per metre of channel length have also been proposed (e.g. Fannin and Wise, 1997).

Detailed mapping of fan deposits can sometimes be interpreted so as to derive a magnitude-cumulative frequency diagram for past debris flow activity (Hungr and Rawlings, 1995). A range of event magnitudes can be derived from the curve, each corresponding to a probability of occurrence. For each class of event, a width and length of damage corridor can be established by runout analysis. The same analysis can be used to estimate hazard intensity parameters including velocity, depth of flow, impact forces and the thickness of deposits. It is then possible to divide the fan area into hazard zones and to specify a range of intensity levels with associated probabilities in each zone. For example, Zone X may be subject to debris flow velocities of 5-10 m/s and depths of 2-3m with a probability of 1 in 500 years or velocities of 1-5m and depths less than 1, at 1 in 50 years. Flooding hazards, determined by a similar procedure, can be superimposed on the same map. Such a map provides sufficient information for hazard acceptance decisions in any part of the fan: a user interested in a certain area can determine what intensity of hazards to expect at a given probability level.

Hazard mapping is much more difficult in connection with debris avalanches, which do not occupy a defined path and deposition area, but may occur at a number of locations within a tract of steep slopes. The hazard study produces zoning which consists of strips of land parallel to the toe of the source slope. The starting point for such a study would be landslide susceptibility mapping for the source slope, using a method similar to the Brabb approach mentioned above. The Geotechnical Engineering Office of the Hong Kong Government has developed such a procedure by analysing a database of some 20,000 debris flows and avalanche events in Hong Kong (Evans and King, 1998). The procedure allows subdividing steep slope areas into susceptibility zones, based on slope and geology, each of which can be can produce an expected number of landslide events per hectare, per year. By summing the areas of susceptibility zones tributary to a project area, it is possible to prepare an estimate of landslide frequency.

The next step in a hazard analysis is to subdivide the expected landslides into magnitude categories, using a magnitude-cumulative frequency curve derived from the same database. Runouts of landslides of different magnitudes are then estimated, using an empirical travel angle approach (e.g. Wong and Ho, 1996), or a dynamic runout analysis (e.g. Hungr, 1995). The resulting runouts are accumulated at the base of the slope to provide an approximate variation of impact probability and intensity with distance from the slope toe (e.g. Tse et al., 1999). The procedure is quite complicated and an exact estimate of spatial probability distribution cannot be claimed. The procedure must therefore be applied with a high degree of conservativism.

Another possibility is to derive estimates of impact probability directly from a careful analysis of existing debris deposits. However, these are frequently very difficult to explore.

Hazard analyses of flow slides and rock avalanches are usually conducted with respect to a specific anticipated event and comprise two steps: estimation of the probability of failure (usually a subjective guess) and a runout analysis. Although a fair number of such assessments have been carried out by consulting engineering geologists in Western Canada, few published accounts exist. A recent example is given by Read et al. (2000).

Hazard acceptance is sometimes based on pre-defined levels of hazard intensity and probability (e.g. Cave, 1992). However, if a clear, thorough and credible hazard characterization is provided in the study report, lay persons should easily be able to establish their own acceptance criteria.

Risk assessment

Determination of risks can be considered as an extension of the hazard study. It is first necessary to determine the elements at risk: human lives, structures and environmental values. An inventory of elements at risk is always required for a risk analysis. If the elements are not yet in existence (i.e. at a projected development site), the risk analysis must begin with a planning study.

Hazard intensity maps prepared in the first stage can be used to estimate impacts on the various elements, using the concept of vulnerability. Input by specialists such as structural engineers may be required at this point. Having subdivided the hazard spectrum into magnitude classes, as described above, we can estimate the damage caused by each class, with it's the associated probability (e.g. Sobkowicz et al., 1995).

The expected material losses can be expressed as rosk costs and assessed by a cost-benefit analysis. Life loss can be compared to published F-N curves (Fell, 1994), which are based on "normal" (tolerable frequency of accidents of various scales.

The success and reliability of risk analyses rests completely on the quality of the hazard assessment completed during the first stage of the process. It is a great challenge of the engineering geology profession to develop more reliable tools for this work. Especially methods of hazard characterization, estimation of probability and runout modelling require substantial improvement.

References

Brabb, E.E. 1991. The world landslide problem. *Episodes*, 14:1, 52-55.

Cave, P., 1992. Hazard acceptability thresholds for development approvals by local government. In *Geologic Hazards in British Columbia*, B.C. Geological Survey Branch Open File 1992-15, Victoria.

Cruden, D.M. and Varnes, D.J. 1996. Landslide Types and Processes. In *Landslides Investigation and Mitigation*. Transportation Research Board, SR 247, Washington, 36-75.

Evans, S.G., and Hungr, O., 1993. The assessment of rockfall hazards at the base of talus slopes. *Canadian Geotechnical Journal*, 30: 620-636.

Evans and King, 1998. Natural Terrain landslide susceptibility. *Tech. Note TN XX/98, Geotechnical Engineering Office*, Hong Kong Government.

Fannin, R.J., and Wise, M.P., 1995. A method for calculation of debris flow travel distance. *Procs., 48th Canadian Geotechnical Conference*, Vancouver, 2:643-650

Fell, R., 1994. Landslide risk assessment and acceptable risk. Canadian Geotechnical Journal, 31:261-272

Hungr, O., 1995. A model for the runout analysis of rapid flow slides, debris flows and avalanches. *Canadian Geotechnical Journal*, 32(4):610-623.

Hungr, O., 1997. Some methods of landslide hazard intensity mapping. *Procs., Landslide Risk Workshop*, R.Fell and D. Cruden, Eds., Balkema, Rotterdam , pp. 215-226.

Hungr, O. and Rawlings, G., 1995. Terrain hazards assessment for planning purposes: Cheekye Fan, B.C. *Procs., 48th. Canadian Geotechnical Conference*, Vancouver, 1: 509-517.

Jackson, L.E. and Kostaschuk, R.A. and MacDonald, G.M., Identification of debris flow hazards on alluvial fans in the Canadian Rocky Mountains. In *Debris Flow: Process, Description and Mitigation*. GSA Reviews in Eng. Geology VII, 115-124.

Mitchell, R.J. and Markell. A.R., 1974. Flow sliding in sensitive soils. *Canadian Geotechnical Journal*, 11:11-31.

Resource Inventory Committee, Government of British Columbia, Victoria, B.C. 1996. Terrain Stability Mapping in BC: A Review and Suggested Methods for Landslide Hazard and Risk Mapping (35pp.)

Sobkowicz, J., Hungr, O. and Morgan, G.C., 1995. Probabilistic mapping of a debris flow hazard area. *Procs., 48th. Canadian Geotechnique Conference*, Vancouver, B.C. 1:519-529.

Read, R.S., Savigny, K.W., Oboni, F., Cruden, D.M. and Lagenberg, C.W., 2000. Geotechnical Hazard assessment of the south flank of Frank Slide, Alberta. Procs., *GeoCanada 2000* (in press).

Tse, C.M., Chu, T., Wu, R., Hungr, O. and Li, F.H., 1999. A risk-based approach to landslide hazard mitigation design. *Procs., Hong Kong Institution of Engineers*, Geotechnical Division Annual Seminar, May 1999, 35-42.

VanDine, D.F. 1985. Debris flows and debris torrents in the southern Canadian Cordillera. *Canadian Geotechnical Journal*, 22:44-68.

Varnes, D.J., 1978. Slope movement types and processes. In *Landslides, Analysis and Control*. Nat. Academy of Sciences, Washington, DC., SR. 176:11-33.

Wong, H.N. and Ho, K.K.S., 1996. Travel distance of landslide debris. *Procs., 7th. International Symposium on Landslides*, Trondheim, 1:417-422.

Snow Avalanche Hazards and Management in Canada: Progress and Challenges

Bruce Jamieson
Adjunct Professor, Department of Civil Engineering
Department of Geology and Geophysics
University of Calgary
Email: *jbjamies@ucalgary.ca*

Impacts

Canada experiences at least 1.5 million potentially destructive avalanches per year (Schaerer, 1984) but only about 100 of these are reported to involve people or property since many occur away from popular recreational or developed areas. Over 600 people have died in snow avalanches in Canada since the mid 1800's, but many early deaths were likely unreported. The activity of avalanche victims has shifted from primarily transportation workers in the 1800's to primarily recreationists in the late 1900's (McFarlane, 1985). Although most avalanche fatalities are in western Canada, there have been at least three residential avalanche incidents resulting in a total of 16 fatalities in Quebec and Newfoundland since 1959 (Jamieson, in press).

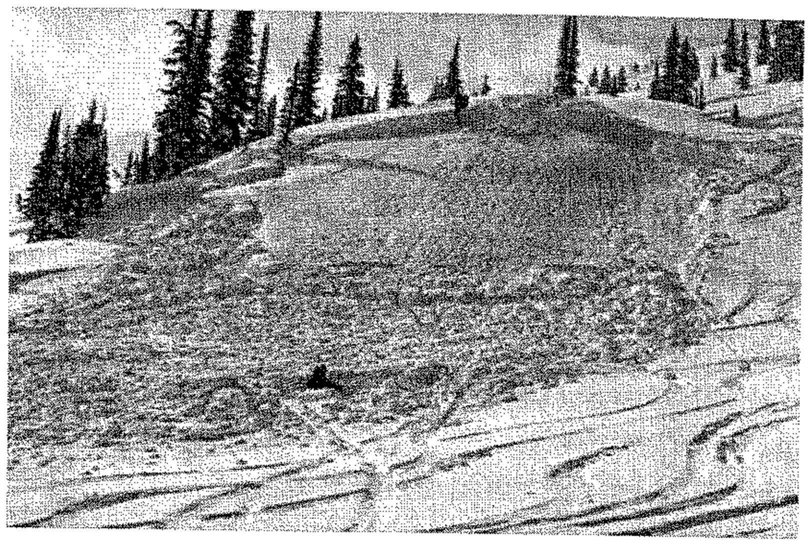


Figure 1. Recreationists may be injured or killed by relatively small avalanches. The risk is usually voluntary but the impact, in terms of human lives, is high.

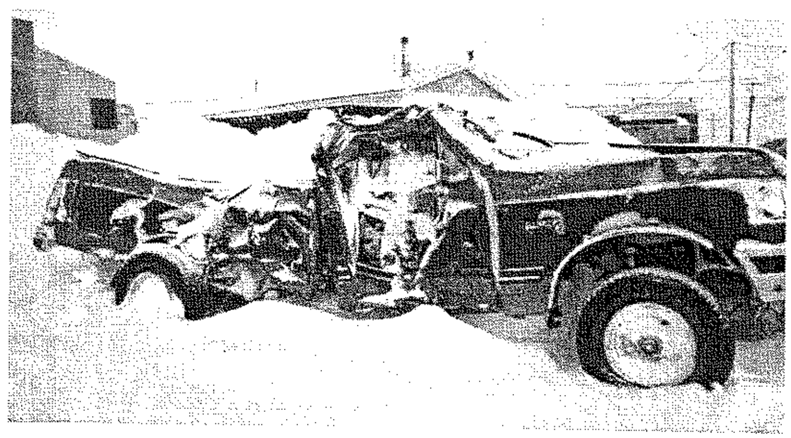


Figure 2. In Canada, snow avalanches rarely kill people on roads. The main effect of avalanches on roads involves delays and consequent loss of business.

In the 1990's, there were 6 to 22 fatalities per year (average 12). Most of the victims were recreationists (Jamieson and Geldsetzer, 1996). Since European society is willing to pay about $2M to save a life (Jóhannesson and others, 1996), the annual impact averages $24M. Only about $0.5M in property damage is reported per year. However, the annual direct cost of avalanche related highway closures exceeds $5M per year. Indirect costs due to business losses would substantially increase the economic impact of delays in transportation corridors but have not been estimated. Damage to forests has not been measured but is probably in the order of several millions of dollars per year. One well documented avalanche that started in a cut block destroyed $400 000 worth of timber and also removed topsoil, thereby inhibiting forest regrowth (McClung, personal communication, 1997). In total, direct avalanche impacts presently average at least C$35M per year. In Canada, avalanche control costs about $10M per year and about $0.5M per year is spent on avalanche research.

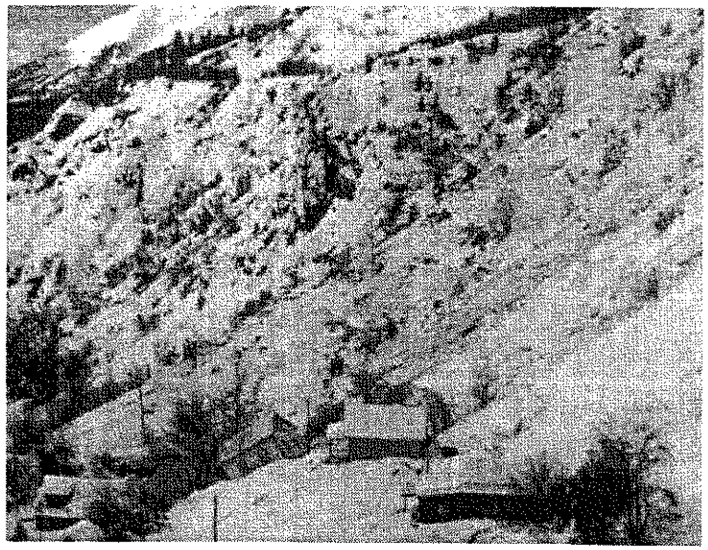


Figure 3. This avalanche struck several houses in Telegraph Creek, BC in 1989 but only one person was killed due to a precautionary evacuation organized by the residents. Jack Bennetto photo.

Hazard Management

For residential areas and public buildings, the avalanche hazard is usually reduced to acceptable levels through hazard mapping and zoning. Defence structures, reinforced buildings and evacuation planning are used in the European Alps but are not common in Canada. Defence structures include snowpack support structures in avalanche start zones, as well as deflecting berms, catchment dams, or avalanche sheds lower in the avalanche path.

For highways, ski lifts and some industrial areas the avalanche risk is reduced through hazard mapping, location planning, defence structures, forecasting, temporary closures and explosive control (Mears, 1992; McClung and Schaerer, 1993). Excluding defense structures, similar methods are used to reduce the avalanche hazard to skiers in developed ski areas and to resource industry workers, where appropriate.

Backcountry recreationists can reduce the avalanche risk by using public avalanche bulletins, taking training courses, being prepared to rescue their companions, travelling with experienced people, and by using weather, snowpack and avalanche observations to select terrain where the avalanche risk is low.

Many decisions including those of backcountry recreationists involve a consideration of perceived risk and perceived benefits. The fact that recreationists are frequently caught or killed in avalanches after they assess the hazard implies they often underestimate the risk. As has been identified for pilots (Transport Canada, 1995) or backcountry recreationists (Fredston and others, 1995), human factors such as impulsiveness or a sense of invulnerability probably contribute to poor risk perception. Recently, relevant material is being added to training courses, videos and books.

Progress

Following the closure of Canada's Avalanche Research Centre in 1991, research programs at the University of British Columbia and the University of Calgary have since developed. These research programs have made important contributions to the study of avalanche formation, spontaneous and human triggered avalanche initiation, statistical avalanche runout, field tests for stability evaluation, avalanche forecasting, avalanche terrain and avalanche risk.

As a result of professional avalanche forecasting and explosive control programs for transportation corridors and ski areas, avalanche fatalities in these areas are now rare.

The Canadian Avalanche Centre started in 1992 as the operations centre of the Canadian Avalanche Association. The Centre exchanges daily weather, snowpack and avalanche information between over 60 avalanche safety programs; trains avalanche professionals; develops avalanche safety books and videos; and provides avalanche bulletins to backcountry users twice a week.

Challenges

Canada has no national or provincial standards for zoning of residential and public buildings. This creates problems for local jurisdictions, land developers, avalanche consultants and ultimately for residents living in and near avalanche areas. Since 1989 there have been three fatal avalanches and 12 deaths in residential or public buildings in Canada. All three occurred on slopes less than 150 m high where avalanches are infrequent. Consequently, municipal planners and residents may have little or no perception of the risk.

Avalanche hazard mapping is challenged by short historical records and uncertainty relating avalanche runout to return intervals. Also, on such short slopes current statistical techniques underestimate the runout and dynamic techniques have not been verified, creating challenges for planners and consultants.

Due to increased development of recreational properties and resource industries such as forestry and mining in mountainous areas, there will be increased need for hazard mitigation and risk management in these areas. Hazard mitigation methods including structural defences – presently more common in Europe – will be required in some locations.

Due to spatial variability of snowpack properties within avalanche start zones and over larger areas as well as practical limitations on explosive avalanche control for large areas of operation, backcountry ski operations continue to face an ongoing challenge. Many of these companies now support research on avalanche formation, initiation and risk.

Few recreationists have been trained to recognize and compensate for the human factors that may affect their decisions in avalanche terrain.

Inadequate funding of the public avalanche bulletin and short-term funding of avalanche research (1-5 years) are ongoing problems but the recently established Canadian Avalanche Foundation may alleviate these concerns.

References

Fredston, J., D. Fesler and B. Tremper. 1995. The human factor - lessons for avalanche education. Proceedings of the International Snow Science Workshop at Snowbird, International Snow Science Workshop 1994, (P.O. Box 49, Snowbird, Utah 84092, USA), 473-486.

Jamieson, J.B. Snow avalanches. A chapter in press for A Synthesis of Geological Hazards in Canada. Bulletin 548, Geological Survey of Canada.

Jóhannesson, T. K. Lied, S. Margreth and F. Sandersen. 1996. An overview of the need for avalanche protection measures in Iceland. Icelandic Meteorological Office Report VI-R96004-UR03, 91 pp.

Jamieson, B. and T. Geldsetzer. 1996. Avalanche Accidents in Canada, Vol. 4: 1984-96. Canadian Avalanche Association, PO Box 2759, Revelstoke, BC, V0E 2S0, 202 pp.

Mears, A.I. 1992. Snow-avalanche hazard analysis for land-use planning and engineering. Colorado Geological Survey, Bulletin 49, 55 pp.

McClung, D.M. and P.A. Schaerer. 1993. The Avalanche Handbook. The Mountaineers, Seattle, p. 271.

McFarlane, R.C. 1985. Snow Avalanche Impacts and Management in Canada. PhD Thesis, University of Waterloo, Waterloo, Ontario, Canada, 272 p.

Schaerer, P.A. 1984. Estimates of the number of avalanches in western Canada. Avalanche News 16, p. 3-6.

Transport Canada. 1995. Human Factors for Aviation – Basic Handbook. Transport Canada TP 12863E, Ottawa, Canada.

Geotechnical Impact of Eastern and Northern Canadian Earthquakes

Maurice Lamontagne
Geological Survey of Canada
7 Observatory Crescent, Ottawa, Ont. K1A 0Y3
Email: *maurice@seismo.nrcan.gc.ca*

Earthquakes in Canada

This paper presents an overview of the history of earthquakes in eastern and northern Canada and of their geotechnical impact.

Numerous large earthquakes have occurred in Canada, in interplate environments of the West as well as in intraplate environments of the North and the East (Figure 1; Table 1). Along the west coast of Canada, plate movements result in significant earthquake activity, including earthquakes larger than magnitude (M)[1] 8 (e.g., the M=8.1 Queen Charlotte Island earthquake of 1949; the M ≈ 9 Cascadia earthquake of January 1700). Although remote from plate boundaries, northern and eastern Canada have also been subject to earthquakes larger than M 5½. In the St. Lawrence and Ottawa river valleys, for instance, damaging earthquakes in the M 5½ to 7 range have occurred in 1663, 1732, 1791, 1860, 1870, 1925, 1935, 1944 and 1988. Fortunately, none of these events caused direct casualties. In 1929, however, 27 people drowned in a tsunami generated by an offshore earthquake of M 7.2 south of Newfoundland. Northern Canada is also the site of M ≥ 5½ earthquakes, including the earthquakes of 1933 in Baffin Bay (M 7.3) and 1989 in the Ungava (M 6.3). Fortunately, the low population density keeps the risk of damage relatively low. A description of large Canadian earthquakes can be found at www.seismo.nrcan.gc.ca

Geotechnical impact

Only a few Eastern Canadian earthquakes of magnitude greater than 5½ have had geotechnical impact. For older events, this may be partly due to the small number of written accounts and to the low population density of some areas. Prior to the 1950's, for instance, geotechnical impacts of Arctic earthquakes could have gone unreported. In this note, geotechnical impact is defined as surface rupture, rock avalanches and rock falls, landslides and slumps in clay deposits, ground cracking, lateral spreading and liquefaction.

[1]M will be used to represent the most widely accepted magnitude for a given event.

The most seismically active region of Eastern Canada is the Charlevoix Seismic Zone (CSZ), with five M ≥ 6 events, in 1663, 1791, 1860, 1870, and 1925. Of these earthquakes, only the 1663 event caused landslides in the epicentral region (Fillion et al., 1991) as well as more than 200 km away, along the Saguenay and St-Maurice rivers (Legget and LaSalle, 1978; Desjardins, 1980). The 1663 could have produced a basin collapse in the Saguenay Fjord (Syvitski and Schafer, 1996). The 1663 and 1870 CSZ earthquakes supposedly caused geysers of water and sand (Dawson, 1870). One possible sand volcano was interpreted in the Gouffre river valley (Chagnon and Locat, 1988). For the other CSZ earthquakes (1791, 1860, 1925), the absence of major geotechnical impact implies that the main shocks were not sufficiently strong or that the failure conditions were not met. The 1925 earthquake, for example, only caused limited cracks in clay deposits (Hodgson, 1945). Although the CSZ is the most seismically active zone of Eastern Canada, a search for a surface rupture caused by these large earthquakes under the St. Lawrence river did not reveal any evidence (Lamontagne, 1999; Section 4.2).

Elsewhere, other M ≥ 5½ earthquakes have had geotechnical impact. The 1929 M 7.2 Grand Banks earthquake triggered a submarine landslide that caused a deadly tsunami on the southern coast of Newfoundland. The 1935 M 6.2 Témiscaming earthquake caused minor rock falls and discoloured lakes near the epicentre and induced the failure of a railway embankment some 300 km from the epicentre (Hodgson, 1945). In the Cordillera, the October 1985 M 6.6 Nahanni earthquake caused a major rock avalanche and rock falls that blocked a river (Wetmiller et al., 1988).

The 1988 M 6.0 Saguenay earthquake produced liquefaction, some rock falls, and landslides as far as 200 km from the epicentre. For the first time, an eastern Canadian earthquake was well recorded by strong ground motion instruments (Munro and North, 1996) and the geotechnical impacts were studied in detail. At 30 km from the epicentre, in the Ferland-Boilleau area, liquefaction caused extensive damage to local houses (Lefebvre et al., 1991; Boivin, 1992). A study of the liquefaction features caused by the 1988 event revealed older liquefaction and ground failure possibly caused by other regional earthquakes (Tuttle et al., 1990). Some failures of railroad and railway embankments were reported as far as 170 km away from the epicentre (Mitchell et al., 1990). Natural slope failures were also reported along the St-Maurice river (Lefebvre et al., 1992).

The 1989 M 6.3 Ungava earthquake occurred close to the surface and caused a 10-km long surface rupture (the first from an historical Eastern North American earthquake), local liquefaction and lake-level change (Adams, 1996).

Smaller events, such as the 1944 Cornwall-Massena earthquake and the 1982 Miramichi earthquake, did not have any geotechnical impact other than drying up some water wells.

Based on what is known of M ≥5½ eastern Canadian earthquakes, the geotechnical implications of these events are as follows. First, the probability of a surface rupture created by such events is small. Most are too small or too deep to cause surface rupture. Second, liquefaction is possible but highly dependent on characteristics of neighbouring unconsolidated deposits. Third, rock falls can occur in regions of steep slopes. Fourth, landslides in clay deposits can occur depending on local conditions existing at the time of occurrence. Fifth, loosely compacted landfills, such as railway embankments, are sensitive to seismic ground motions even at large distances from the epicentre. Finally, evidence of past large earthquakes, such as sand dykes, may be found in unconsolidated deposits that record liquefaction (Adams, 1996).

Earthquake Damage in eastern Canada

In the past, destructive earthquakes have occurred in eastern Canada and similar events will undoubtedly happen in the future. The exact time and place of these events cannot be predicted; only the areas most likely to be affected by the strong motions can be predetermined. Previous experience has stressed several lessons useful for seismic hazard and seismic risk studies. Due to the efficiency of the Canadian Shield to carry seismic waves, moderate to large eastern Canadian earthquakes can be felt over large distances (more than 1000 km for magnitude 6 earthquakes) and damage is not constrained to the epicentral region.

Remote from the epicentral region, damage is more common in buildings with unreinforced masonry elements that reside on thick clay deposits. These aspects of damage distribution were first recognized after the 1925 Charlevoix earthquake (Hodgson, 1945) and confirmed in subsequent eastern Canadian earthquakes.

Some eastern Canadian earthquakes severely damaged buildings with unreinforced masonry elements. From photographic documentation of XXth centry earthquakes, out-of-plane failure has been the most frequently reported form of damage to these buildings, in agreement with current knowledge on the behaviour of such structures (Bruneau and Lamontagne, 1994). Damage can also be controlled by foundation type, quality of construction, exterior facade and its fastening to the structure (Paultre et al., 1993).

Damage can be locally enhanced by the type of overburden (Hodgson, 1945; Paultre et al., 1993). In almost all cases of earthquake damage, buildings were resting on soft soils (clay, sand, fill).

In the case of the Saguenay earthquake, 95% of all damage were associated with soft soils (53% with clay, 24% on multi-layer, and 18% on sand). It was also found that damage for buildings on sandy foundations were restricted to 150 km epicentral distance whereas for clay foundations, damage existed up to 350 km distance (Paultre et al., 1993). Obviously, the type of foundation largely determines the extent of earthquake damage.

Damage seen in historical earthquakes is likely to repeat during comparable future earthquakes. Widespread urban and industrial developments have taken place on soils now recognized as capable of amplifying earthquake ground motions. The presence of old buildings coupled with the population growth make earthquakes a significant threat in eastern Canada. Microseismic zonation of urban areas and improved account of soil amplification in the next National Building Code of Canada may provide partial answers on the extent of the problem.

Acknowledgments

I thank Stephen Halchuk for the material appearing in Figure 1 and J. Adams for useful additions to the paper.

References

Adams, J. 1996. Paleoseismology studies in Canada - a dozen years of progress: Journal of Geophysical Research, v. 101, p. 6193-6207.

Anglin, F.M., Wetmiller, R.J., Horner, R.B., Rogers, G.C., and Drysdale J.A. 1990. Seismicity Map of Canada, Geological Survey of Canada, Canadian Geophysical Atlas, Map 15 with descriptive notes, scale 1:10 000 000.

Boivin, D.J., 1992. Analyse et cartographie des dommages du séisme survenu au Québec le 25 novembre 1988. The Canadian geographer /Le géographe cananadien, 36, no. 2, 114-123.

Bruneau, M. and Lamontagne, M. 1994. Damage from 20th century earthquakes in eastern Canada and seismic vulnerability of unreinforced masonry buildings. Can. J. of Civil Engineering, 21, no. 4, p. 643-662.

Chagnon J.-Y. and Locat, J. 1988. The effects of seismic activity on the soils of the Charlevoix area - Quebec, Canada. M.I. El-Sabh and T.S. Murty (eds.). Natural and Man-Made Hazards, 125-136.

Drysdale, J. and Cajka, M., 1989. "Intensity Report of the November 25, 1988 Saguenay, Quebec Earthquake.". GSC Open File Report #3279.

Filion, L., Quinty, F., and C. Bégin. 1991. A chronology of landslide activity in the valley of Rivière du Gouffre, Charlevoix, Québec, *Can. J. Earth. Sci., 28*, 250-256.

Hodgson, E.A., 1945. Industrial earthquake hazards in eastern Canada. Bulletin of the Seismological Society of America, v. 35, No. 4, 151-174.

Lamontagne, M. 1999. Rheological and Geological Constraints on the Earthquake Distribution in the Charlevoix Seismic Zone, Québec. Geological Survey of Canada Open File Report D3778, 1 CD-ROM.

Lefebvre, G., Paultre, P., Devic, J.-P., and G. Côté. 1991. Distribution of damages and site effects during the 1988 Saguenay earthquake, Proceedings of the 6th Canadian Conf. Earthquake Engineering, Toronto 1991, 719-726.

Lefebvre, G., Leboeuf, D., Hornych, P., and Tanguay, L. 1992. Slope failures associated with the 1988 Saguenay earthquake, Quebec, Canada. Canadian Geotechnical Journal, 29(1): 117-130.

Mitchell d., Tinawi, R., and T. Law, 1990. Damaage caused by the November 25, 1988 Saguenay earthquake. Can. J. of Civil Eng. 17, no. 3, 338-365.

Munro, P.S., North, R.G., 1988. The Saguenay earthquake of November 25, 1988: Strong motion data, Geological Survey of Canada Open File Report 1976.

Paultre, P., Lefebvre, G., Devic, J.-P., and Côté, G. 1993. Statistical analyses of damages to buildings in the 1988 Saguenay earthquake, Can. J. of Civil Eng., 20, 988-998.

Syvitski, J.P.M., and Schafer, C.T. 1996. Evidence for an earthquake basin-triggered basin collapse in Saguenay Fjord, Canada. Sedimentary Geology 104, 127-153.

Tuttle, M., Law, K.T., Seeber, L. and Jacob, K., 1990. Liquefaction and ground failure induced by the 1988 Saguenay, Quebec, earthquake. Can. Geotech. J., 27, 580-589.

Wetmiller, R.J., Horner, R.B., Hasegawa, H.S., North, R.G., Lamontagne, M., Weichert, D.H., Evans, S.G. 1988. "An analysis of the 1985 Nahanni earthquakes", Bulletin of the Seismological Society of America, vol. 78, no. 2, p. 590-616.

Figure 1. Seismicity of Canada and surrounding regions in the period 1568 to 1998 (updated from Canadian Geophysical Atlas, Anglin et al., 1990). Stars are epicentres of earthquakes discussed in text. The map presents a selection of earthquakes from the Canadian Earthquake Epicentre File. Earthquakes are selected on a basis which lessens the impact of the uneven reporting of historical earthquakes. Prior to the beginning of the 20th century, earthquakes could only be documented by written accounts and only in the inhabited parts of the country, i.e. a small portion of the territory. Earthquake coverage improved rapidly with the introduction and subsequent improvements of the Canadian seismograph network.

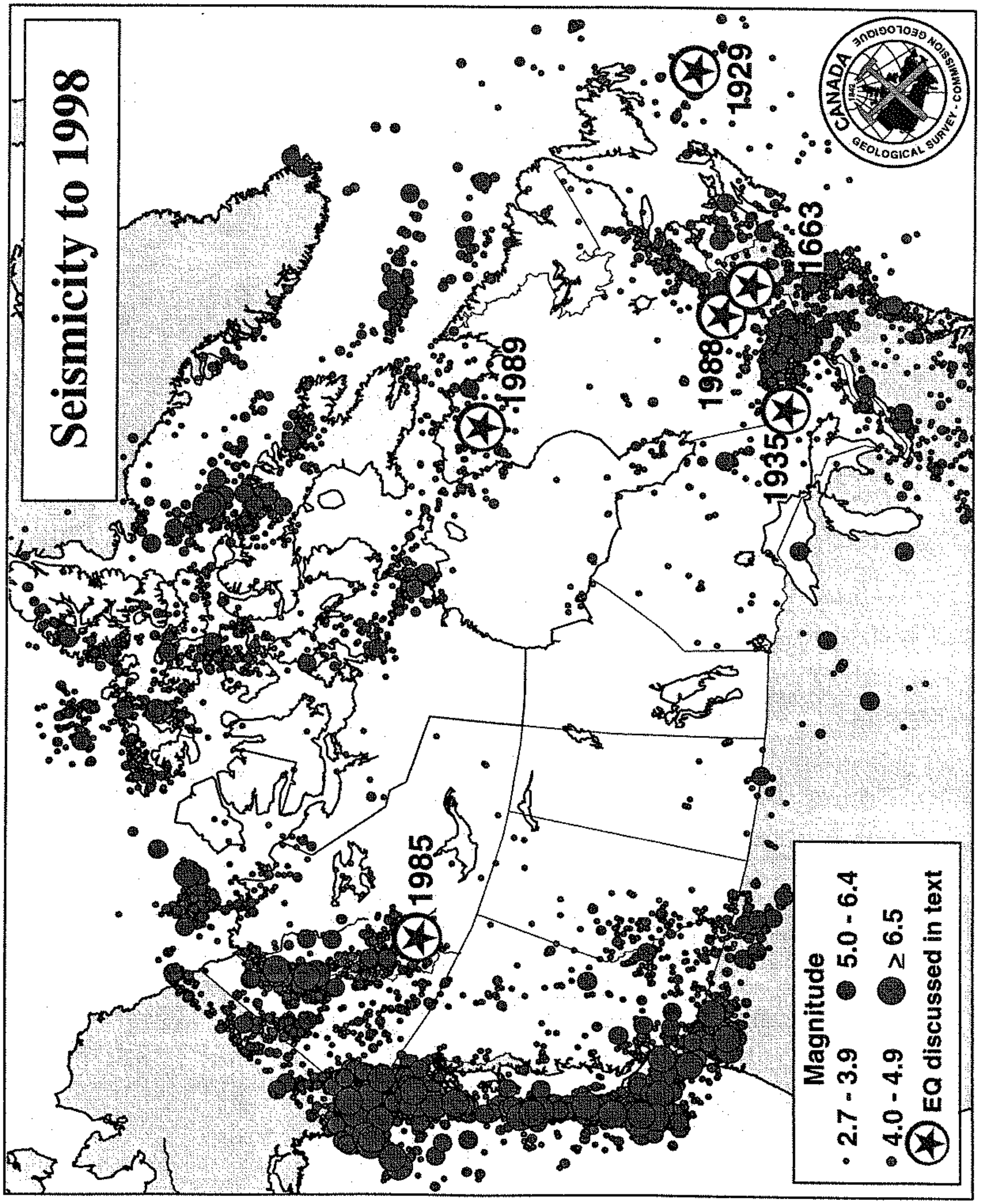

Seismicity to 1998
1929
1663
1988
1989
1935
1985
Magnitude
2.7 - 3.9
4.0 - 4.9
5.0 - 6.4
≥ 6.5
EQ discussed in text
CANADA
GEOLOGICAL SURVEY · COMMISSION GEOLOGIQUE

Table 1: Some Significant Eastern and Northern Canadian Earthquakes 1600-1999.

Year	Date	Lat(° N)	Lon (°W)	Magnitude[2]	Geotechnical impact	Comments
1663	5 February	47.6	70.1	≈7	Landslides in Charlevoix, Saguenay and Mauricie.	Charlevoix-Kamouraska Region
1732	16 September	45.5	73.6	≈5.8	None reported	Montreal Region
1791	6 December	47.4	70.5	≈6	None reported	Charlevoix-Kamouraska Region
1860	17 October	47.5	70.1	≈6	None reported	Charlevoix-Kamouraska Region
1870	20 October	47.4	70.5	≈6½	Possible liquefaction	Charlevoix-Kamouraska Region
1925	1 March	47.8	69.8	6.5	Open cracks in clay	Charlevoix-Kamouraska Region
1929	18 November	44.5	56.3	7.2	Submarine landslide; tsunami	Atlantic Ocean, south of Newfoundland
1933	20 November	73.0	70.7	7.3	None known	Baffin Bay, Nunavut
1935	01 November	46.8	79.1	6.2	Fallen rocks; discoloured lake; embankment slide	Quebec - Ontario Border, Temiscamingue region
1944	05 September	45.0	74.9	5.6	None	Cornwall region, Ontario-New York border
1982	09 January	47.0	66.6	5.7	None	Miramichi Highlands, N.B.

[2]Since pre-20th century earthquakes were not instrumentally recorded, their locations and magnitudes are evaluated from felt reports and descriptions of damage.

Year	Date	Lat(° N)	Lon (°W)	Magnitude[3]	Geotechnical impact	Comments
1985	05 October	62.2	124.2	6.6	Rock avalanche; rock slides	Nahanni region, Northwest Territories
1985	23 December	62.2	124.2	6.9	Rock slides	Nahanni region, Northwest Territories
1988	25 November	48.1	71.2	6.0	Landslides; embankment slides; liquefaction	Saguenay region, Quebec
1989	25 December	60.1	73.6	6.3	Surface rupture; liquefaction	Ungava region, Quebec

[3]Since pre-20th century earthquakes were not instrumentally recorded, their locations and magnitudes are evaluated from felt reports and descriptions of damage.

Geo-hazards in Sensitive Clays and a Review of the 1971 St. Jean Vianney Mudflow

Jacques Locat
Department of Geology and Geological Engineering, Laval University
Sainte-Foy, Qc, Canada, G1K 7P4
Email: locat@ggl.ulaval.ca

Introduction

Sensitive clays have been studied over many years and are still of great interest, not only because of their unique nature and behaviour, but also by the threat that they still pose to human life and activities. Sensitive clays are typically found in the Northern Hemisphere and particularily in areas where metamorphic terrain has been eroded by glaciers (Scandinavia, Russia and parts of Canada, Locat 1995).

Nature and Sedimentary Environments

Our observation about the distribution of so-called "sensitive clays" indicates that they are mostly made of material which consist of rock flour eroded from metamorphic terrain. For example, if we look at the St. Lawrence Lowlands, we can see that the Champlain Sea clays are found over a wide area. This basin is limited to the south by the Appalachian Mountains and to the north by the Laurentian Plateau. Although the distribution itself has never been done rigorously, it appears that most of the very sensitive clays, i.e. provide typical mudflow behaviour, are found along the foothills of the Laurentian Plateau. In fact, we find them all around the Precambrian Shield. From the work of Quigley (1980), Torrance (1983) and Locat (1995) it is clear that the conditions for this high sensitivity to develop are the following:

- Rock flour from metamorphic terrain.
- Deposition in sea water of low salinity (because of meltwater proximity) and organic matter (may be also high sedimentation rate).
- Land emergence and leaching to a salinity value less than 2 g/L.

Geotechnical Properties

Geotechnical properties of sensitive clays are the result of the above mentioned processes. It is best explain by the use of SEDON (SEDimentation-CONsolidation) tests (Locat 1982; Perret 1995). These types of tests re-produce in the laboratory the condition typical of rapidly deposited sediments, like turbidites. The final product is a clay with a low activity, low plasticity, low organic content, relatively high specific surface area, high compressibility, low remoulded shear strength or high liquidity index.

Rheological Properties

These unique geotechnical characteristics are essential for the development of the mobility of this type of clay when a slide or a mudflow takes place. We can directly relate the liquidity index to mobility, both for the retrogression (Lebuis et al. 1983) and run out (Locat 1997; Leroueil and Locat 1998). Lebuis et al. (1983) have shown that we could define a relationship providing a threshold value for retrogression to take place. Therefore, the liquidity index is a good predictor of the rheological properties of the sediment, like the yield strength and the viscosity.

Type of Failures and Their Extent

Most of the types of failure are present in sensitive clays, from single slump to the rapidly moving mudflow. In most cases, we can consider two situations: (1) the remoulded soils is confined within the slide area (St. Boniface slide of 1996) or (2) it can rapidly be taken away downstream from the slide area (St. Jean Vianney slides).

Finally the paper will present a discussion of the 1971 St. Jean-Vianney landslide (Figures 1 and 2) and an overview of landslide hazard and risk assessment. The landslide took place in two distinct events (April 22nd and May 4th 1971). The local morphology provided easy evacuation of the remoulded material so that a large retrogression could take place. The base of the failure plane could have been controlled by the rapid change in the liquidity index as found at a depth of about 25m were the salinity returns to values closer to marine conditions (Figure 2). As for the 1663 landslide, the 1971 mudflow produced a distinct layer in the Bras Nord of the Saguenay fjord that is now used as a 1971 marker horizon !

Acknowledgements

This work has been sponsored by grants from the Québec Ministry of Education, Fonds F.C.A.R. and by the National Sciences and Engineering Research Council of Canada. I would like also to thank the participation of many students and colleagues of Laval University and elsewhere.

References

Lebuis, J., Robert, J.-M., and Rissmann, P., 1983. Regional mapping of landslide hazard in Québec. In: Proceedings of the International Symposium on slopes on soft clays, Linkoping, Swedish Geotechnical Institute *Report, No. 17: 205-262.*

Leroueil, S. and Locat, J., 1998. Geotechnical characterization, risk assessment and mitigation. Proceedings of the XI Danube-European Conference on soil Mechanics and Geotechnical Engineering, *Porec, Croatia.12 p.*

Locat, J., 1982. Origine de la surconsolidaiton des argiles sensibles de l'Est du Canada. Ph. D. Thesis, Department of Civil Engineering, University of Sherbrooke, *Québec, Canada.*

Locat, J. 1995. On the development of microstructure in collapsible soils: lessons from the study of recent sediments and artificial cementation. In: E. Derbyshire et al. 9eds), Genesis and Properties of Collapsible Soils, *Kluwer Academic Publisher, 93-128.*

Locat, J., 1997. Normalized rheological behaviour of fine muds and their flow properties in a pseudoplactic regime. In: Proceedings the ASCE Conference on Debris-Flows Hazards Mitigation: Mechanics, Prediction, and Assessment, *San Francisco, pp.: 260-269.*

Perret, D. 1995. Étude du développement de la résistance au cisaillement dans un sédiment récent. Ph. D. Thesis, Department of Geology and Geological Engineering, Laval University, *Québec, Canada.*

Quigley, R.M., 1980. Geology, Mineralogy and geochemistry of Canadian soft soils: a geotechnical perspective. Canadian Geotechnical Journal, *17: 261-285.*

Torrance, J.K., 1983. Towards a general model of quick clay development. Sedimentology, *30: 547-555.*

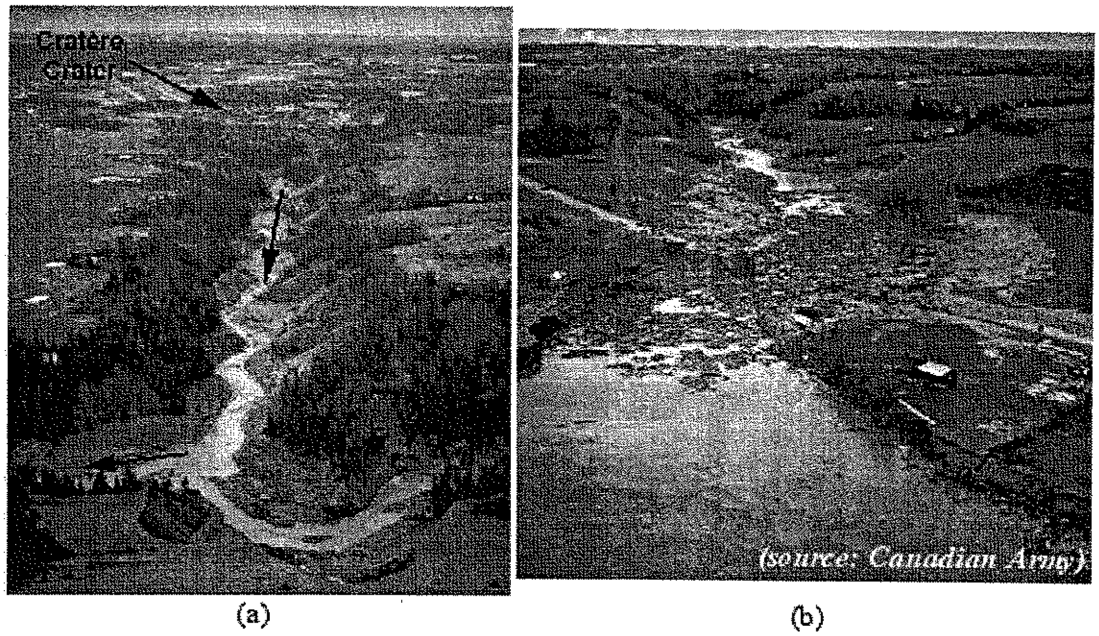
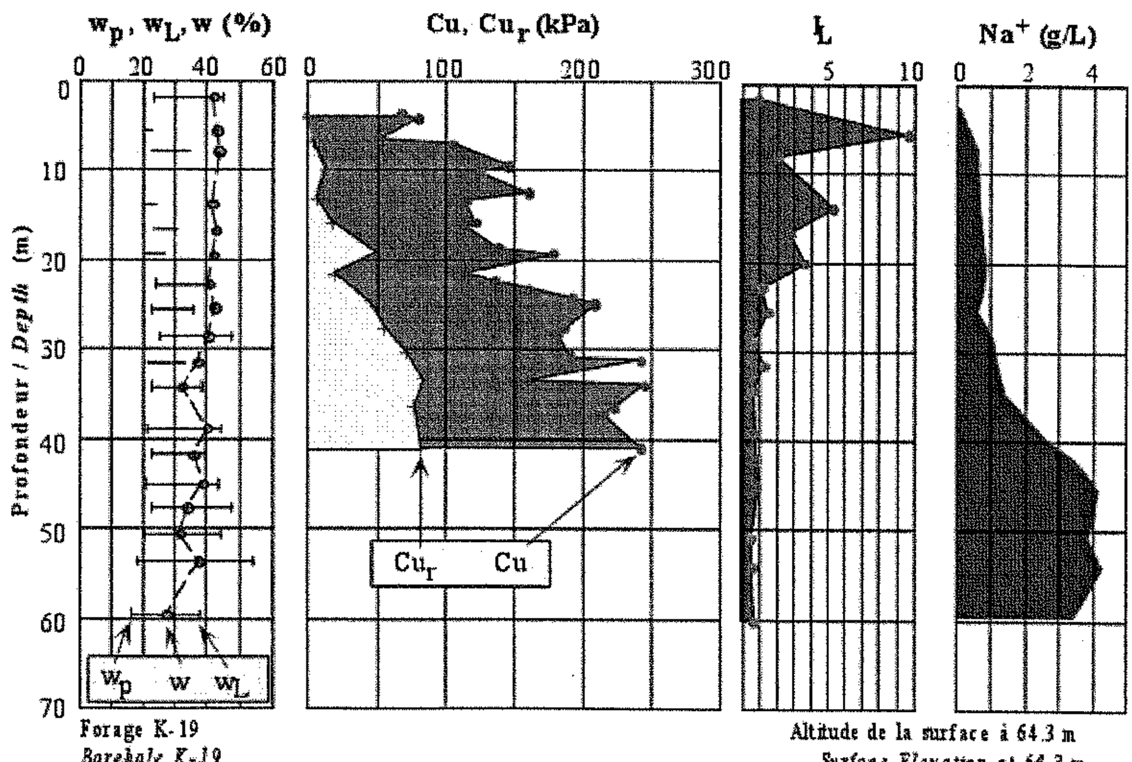


Figure 1. Oblique views of the St. Jean -Vianney mudflow taken on May 4th 1971

Figure 2. Profil géotechnique de l'argile de Saint-Jean Vianney
Geotechnical Profile of the St.-Jean Vianney Clay



A Review of Some Tsunamis in Canada

Tad S. Murty

W.F. Baird & Associates Coastal Engineers Ltd.
1145 Hunt Club Road, Suite 1, Ottawa, Ontario K1V 0Y3, Canada
E-mail: *tmurty@baird.com*

Tsunamis have occurred in Canada due to under ocean earthquakes, submarine land slides and even from large human made explosions. Geographically these events took place on the Pacific coast, the St. Lawrence Estuary, Nova Scotia and in Newfoundland. In the twentieth century the following is a partial chronological list of tsunamis in Canada.

1. December 6th, 1917: Large tsunami in the Halifax Harbour due to an explosion. (Figure 1) (Greenberg et al, 1993, 1994; Ruffman et al, 1995).

2. November 18th, 1929: Large tsunami in Burin Inlet due to an earthquake off the coast of Newfoundland (Figure 2) (Murty, 1977).

3. June 23, 1946: Small tsunami in the Strait of Georgia due to an earthquake on the Vancouver Island (Murty and Crean, 1986).

4. March 28th 1964: Large tsunami on the coast of British Columbia due to an earthquake in Alaska (Dunbar et al, 1989 a,b).

5. April 27, 1975: Large tsunami in Kitimat Inlet due to a submarine landslide (Murty, 1979; Murty and Brown, 1979).

All of these tsunamis have quite different characteristics as can be seen below. During the First World War, a munitions ship caught fire and exploded in Halifax harbor on December 6th, 1917. In the harbor narrows the amplitude of the tsunami that was generated was about ten meters in amplitude.

The Grandbanks earthquake of November 18th, 1929 created a tsunami of at least 12.2 meters in amplitude in the Burin Inlet. Some estimates put the maximum amplitude at about 35 meters. The turbidity currents following the earthquake caused numerous cable breaks in the Atlantic Ocean. On June 23, 1946, a small tsunami occurred in the northern part of the Strait of Georgia (between Vancouver Island and the main land) following an earthquake on Vancouver Island close to the western shore of the Strait.

Following a large earthquake in Alaska on March 28th, 1964, a major Pacific wide tsunami was generated. Outside of Alaska, the largest tsunami amplitude anywhere on the west coast of North America occurred not exactly on the open coast, but inland at Port Alberni at the head of the Alberni Inlet. This can be explained as due to the amplification of the tsunami through quarter wave resonance as the tsunami traveled from the mouth to the head of the inlet.

On April 27, 1975, following a major submarine land slide, a tsunami was generated in the Kitimat Inlet in the Douglas Channel system of the northern part of the coast of British Columbia.

References

Dunbar, D., P.H. LeBlond and T.S. Murty (1989a). Evaluation of tsunami amplitudes for the Pacific coast of Canada. Progress in Oceanography, 26, 115-177.

Dunbar, D., P.H. LeBlond and T.S. Murty (1989b). Maximum tsunami amplitudes and associated currents on the coast of British Columbia. Science of Tsunami Hazards, 7(1), 3-44.

Greenberg, D.A., T.S. Murty and A. Ruffman (1993). A numerical model for the Halifax Harbor tsunami due to the 1917 explosion. Marine Geodesy, 16(2), 153-168.

Greenberg, D.A., T.S. Murty and A. Ruffman (1994). Modeling the tsunami from the 1917 Halifax Harbor explosion. Science of Tsunami Hazards, 11(2), 67-80.

Murty, T.S. (1977). Seismic sea waves-tsunamis, Bull. 198, FisheriesResearch Board of Canada, Ottawa, 337 pages.

Murty, T.S. (1979). Submarine slide-generated water waves in Kitimat Inlet British Columbia. J. Geo. Phys. Res., 84(C12), 7777-7779.

Murty, T.S. and P.B. Crean (1986). Numerical simulation of the tsunami of June 23, 1946 in British Columbia, Canada. Science of Tsunami Hazards, 4(1), 15-24.

Murty, T.S. and R.E. Brown (1979). The submarine slide of 27 April, 1975, in Kitimat Inlet and the water waves that accompanied the slide. Pacific Marine Science Report 79-11, Institute of Ocean Sciences, Sidney, B.C., Canada, 36 pages.

Ruffman, A., D.A. Greenburg and T.S. Murty (1995). The Tsunami from the Explosion in Halifax Harbour, Ground Zero, 327-344. Ed: A. Ruffman and C.D. Howell. Nimbus Publishing Ltd Halifax.

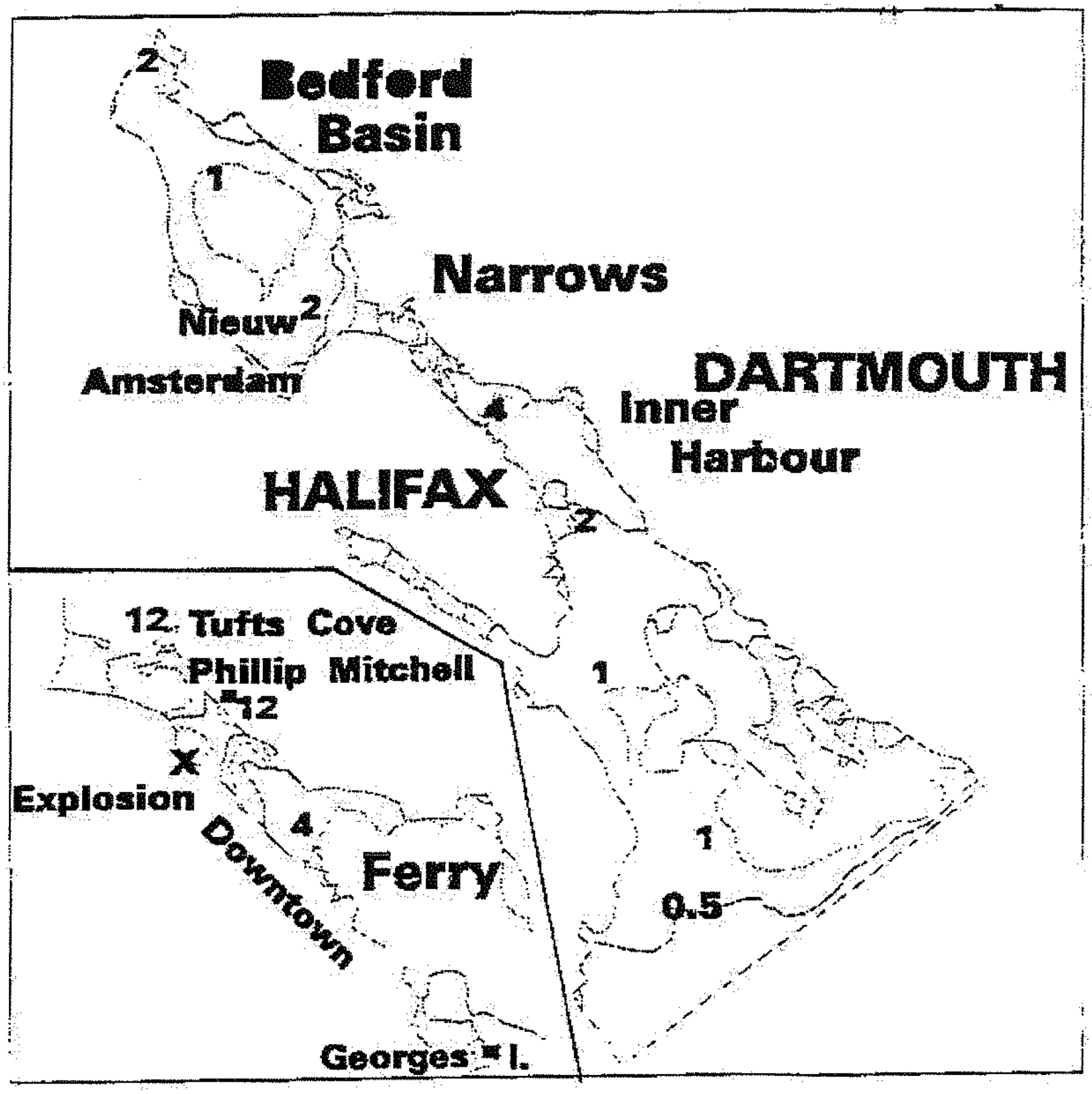


Figure 1. *The maximum elevation (m) achieved during the model run and locations (estimated) of the anecdotal observations. The detail of the Narrows is shown in the lower left.*

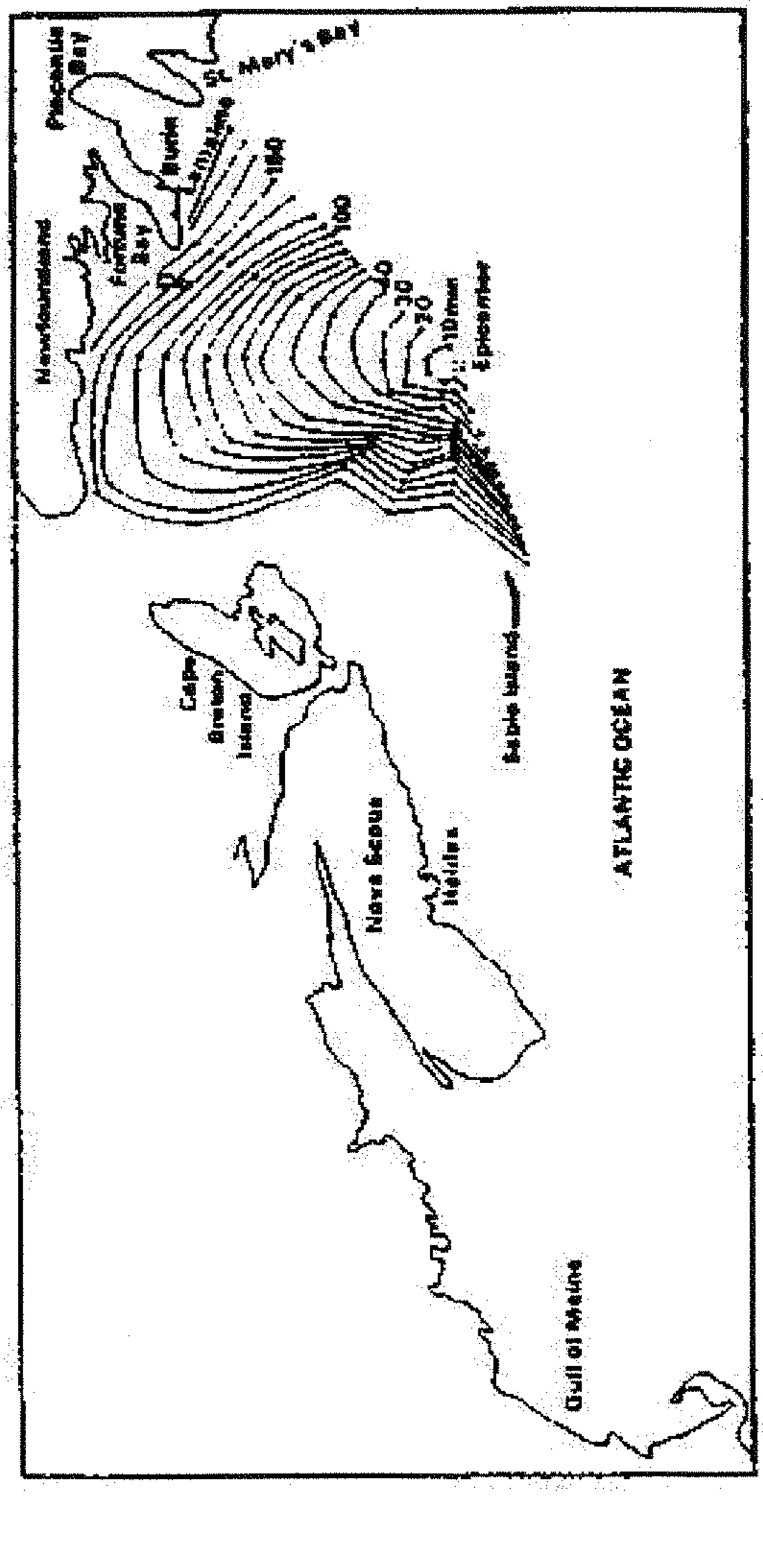


Figure 2. Travel-time curves (minutes) for the Grand Banks earthquake tsunami of Nov. 18, 1929.

NHEMATIS: Progress on a Natural Hazard Risk Assessment Model

Christopher Tucker
Senior Scientific Advisor, Emergency Preparedness Canada
122 Bank Street, 2nd Floor, Ottawa, ON, Canada, K1A 0W6.
Email: *ctucker@epc-pcc.gc.ca*

Grace Koshida
Scientific Advisor, Office of the Senior Scientific Advisor, Emergency Preparedness Canada
122 Bank Street, 2nd Floor, Ottawa, ON, Canada, K1A 0W6.
Email: *Grace.Koshida@epc-pcc.gc.ca*

Timothy M. Webb
President, Lookfar Solutions Inc.
P.O. Box 811, 1232 Lynn Road, Tofino, BC V0R 2Z0.
Email: *twebb@island.net*

Emergency Preparedness Canada (EPC), in cooperation with public and private sector partners, has been conducting extensive research on risk assessment and vulnerability to natural hazards in Canada. Its major research effort over the past six years is the National Hazards Electronic Map and Assessment Tools Information System (NHEMATIS), comprising an electronic natural hazards map of Canada and a series of risk assessment/search and query tools.

NHEMATIS is a modern computerized system for data capture, storage, presentation, hazard assessment and modelling. By combining the power of expert system technology with the spatial analysis capabilities of a geographic information system (GIS), NHEMATIS provides a repository of information on historical and potential future disasters, an inventory of information on facilities and people at risk to natural hazards, and tools and algorithms for estimating the damage that could be caused by various natural hazard events.

The core technologies used and developed for NHEMATIS include: the ArcView desktop GIS system from ESRI, the Microsoft Access relational database system, the Calyx GIS expert system engine from Nobility, and the Crystal Reports report generation system; customization and linking of these technologies was done using the C++ programming language and the Avenue scripting language for controlling ArcView (Figure 1) (Tucker and Webb, 1998; Webb, 1999).

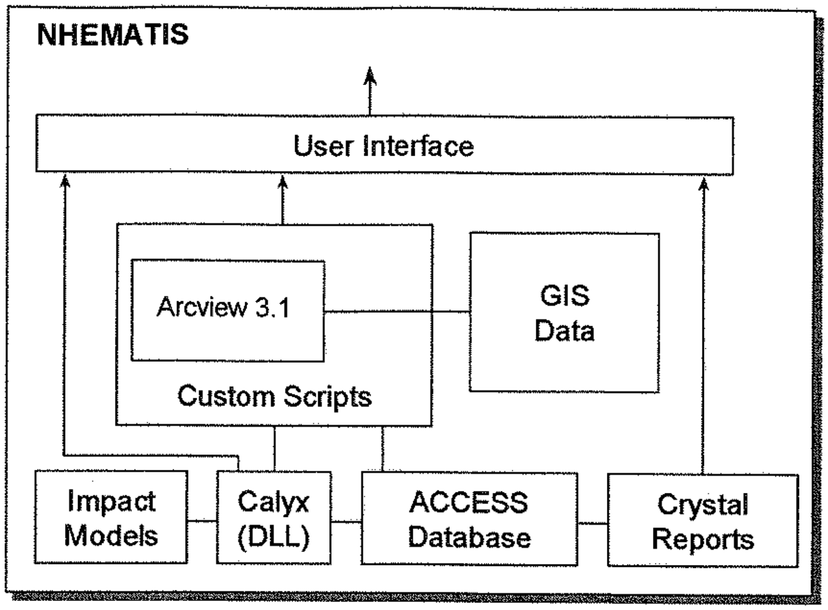


Figure 1. NHEMATIS structural components

The original release of NHEMATIS (version 0.4) was completed in 1999 and is available on CD-ROM, along with a Technical Manual and a User's Guide. Version 0.4 of NHEMATIS contained all of the data collected during the four-year development phase and required a larger amount of disk space and RAM to operate. Hardware requirements for running NHEMATIS included a Pentium CPU, over 600 MB of disk space, a CD ROM, and 64 MB of RAM.

Webb *et al.* (1999) states that the Calyx GIS Inference Engine consists of the following standard components:

a. The Calyx Inference Engine, which works with information contained in the associated database to determine the potential for different types of impacts. The inference engine is composed of a series of executable routines that can be accessed from a third party interface. and are executed as a "black box" process by a host user interface. The result of their execution is the determination of impacts and their associated significance based upon actual scenario and site data entered by the end user and stored in the database.

b. The Calyx GIS Interface module that allows the Calyx Inference Engine to communicate with the ArcView desktop GIS system in order to automatically trigger geographic queries to resolve the spatial relationships between geographically explicit entities.

c. The Calyx User Interface that provides a set of standard user interface components including dialog boxes, menus, windows, screens, and report generation modules that allow the user to work with the Calyx Inference Engine in a standard fashion.

NHEMATIS currently contains national geographic databases as well as detailed datasets for four local study areas (Vancouver, Edmonton, Montreal, Ottawa) for demonstration purposes. In a typical study area, the following map layers have been extracted as facilities subject to damage calculations: built-up areas (as polygons and points), roads, railways, bridges, tunnels, power lines and pipelines. Additional map layers used for georeferencing and display purposes include land use maps, Geological Survey of Canada soils map, historical earthquakes, lakes, rivers, streams, and contours.

The core function of NHEMATIS involves the simulation and analysis of natural hazards (earthquakes, floods, tornadoes and landslides) for the four study areas. From a user's point of view, Webb (1999) identifies the following steps:

a. ***Hazard specification*** - Description of the hazard scenario. This can involve background research and discussion with experts.
b. ***Initial hazard calculation*** - In this step, the user takes the hazard that they have specified (earthquake of a particular type in a certain location) and calculates the degree of hazard in the form of a map for their community. This results in maps of factors such as MMI or Fujita wind levels. This step is quite efficient and can be useful on its own as a rapid filter for examining a wide range of different scenarios.
c. ***Impact rate calculation*** - This step utilizes various models and expert system elements to generate spatially explicit impact rates for all of the different facilities being considered.
d. ***Report and map creation*** - Once impact rate maps have been constructed the results are used, along with cartographic output maps of facility density, population, etc. to produce maps and reports of actual losses. These are presented in terms of rates or densities measured in units of floorspace, dollars, injuries, and mortalities.

NHEMATIS utilizes a simple but effective method for the prediction of damage levels for a wide range of different types of facilities. The analysis results in a damage algorithm that uses a simple sigmoid relationship to predict damage with just two main parameters that can be estimated based on either empirical data or expert judgement. This damage algorithm is used throughout NHEMATIS and allows the current system to be rapidly configured for a new study area with minimal data (Webb, 1999).

The sigmoid damage algorithm is a unique feature of NHEMATIS and helps to define its role in hazard analysis. Because this approach is so easy to parameterize, it is well suited to situations where data on detailed building design and response is scarce and where predictions of damage need to be made across a large number of buildings in an area. This situation is common in

Canada where the building stock is often not well-characterized (e.g., residential buildings in a certain segment of a city may all be one to two stories and wood construction but the details of design and age may be totally unknown) (Webb, 1999).

For example, to run an earthquake scenario for Vancouver, NHEMATIS simulates the damage expected from the earthquake event by first generating a map of strong ground motions using relationships (equations) that describe how Peak Ground Acceleration (PGA) attenuates with distance; PGA is then converted to a measure of damage intensity in units of the Modified Mercalli Index (MMI); and finally, the damage expected for different building types is estimated for each level of MMI (Figure 2).

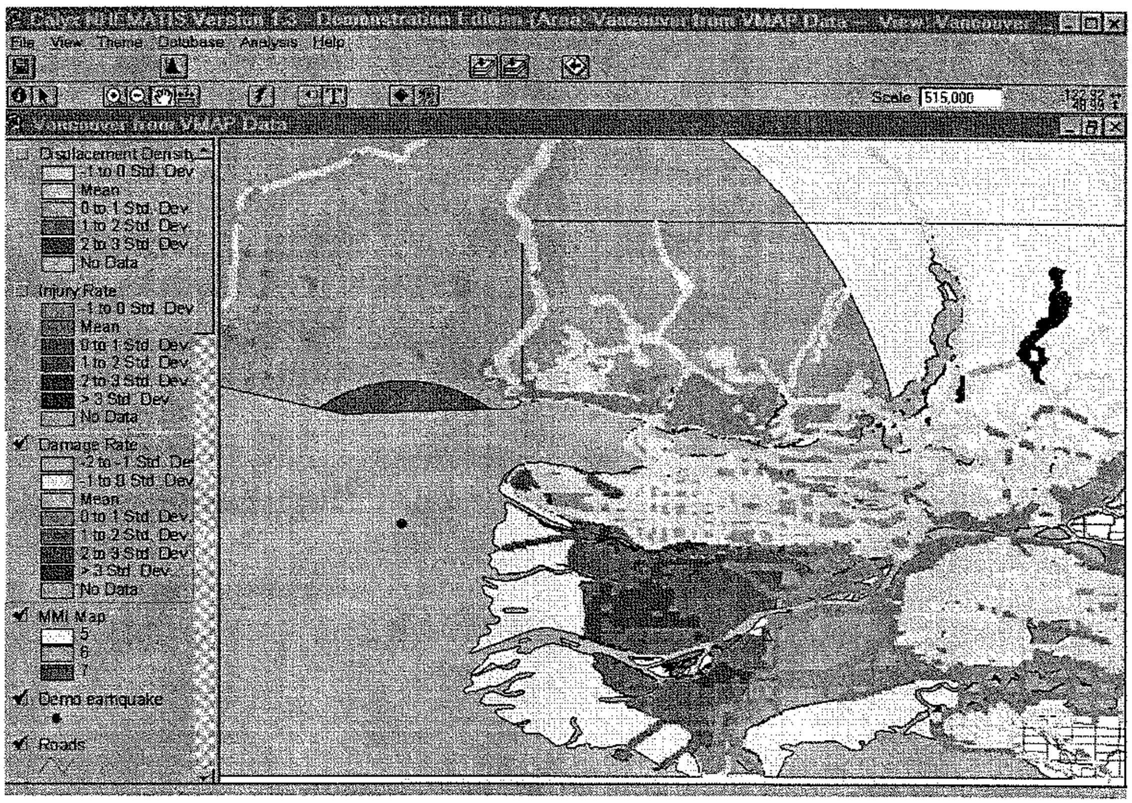


Figure 2. MMI map (6.5 Richter earthquake, 20-30 km depth) and related damage density map for the Vancouver study area.

Recent work over the past year has resulted in the production of a number of versions which further enhance the functionality, profile and implementation of NHEMATIS in three areas (Tucker *et al.*, 1999; Webb, 2000a; Webb, 2000b).

First, in order to strengthen the core functionality of NHEMATIS, the different equations available and commonly used for earthquake attenuation were reexamined. Historical maps of estimated MMI (Modified Mercalli Index) were obtained for a range of events in eastern and western Canada and improved sets of equations and parameters were built into the NHEMATIS software (Webb, 2000b).

Second, training versions of NHEMATIS were developed during the autumn 1999/winter 2000 semester to evaluate the suitability of NHEMATIS as an educational tool. NHEMATIS was used in two laboratory assignments in an upper-year undergraduate geography course at Carleton University in Ottawa (Brklacich, 2000). Student user and faculty feedback will hopefully lead towards the development of a final training version of NHEMATIS for educational purposes.

Finally, a prototype World Wide Web application to deliver key components of NHEMATIS functionality is being developed to advance public awareness of risk and vulnerability concepts.

NHEMATIS Web site

http://www.nobility.com/apps/emerg/index_fr.htm

References

Brklacich, M., 2000. *Preliminary assessment of the Natural Hazards Electronic Map and Assessment Tools Information System (NHEMATIS) as an Educational Tool: Final Report.* A report prepared for Emergency Preparedness Canada. 43 pp.

Tucker, C. and Webb, T. M., 1998. "Risk Assessment and Natural Hazards in Canada", *GIS World*, May 1998, pp. 223-226.

Tucker, C., Webb, T.M. and Koshida, G., 1999. *Near-term spatial data set needs for risk assessment and natural hazards research at Emergency Preparedness Canada*, Spatially Oriented Referencing Systems Association (SORSA) Workshop Proceedings, SORSA99 workshop held at the University of Ottawa, August 11-14, 1999, http://aix1.uottawa.ca/~ddouglas/s99proc/s99toc01.htm, 13 pp.

Webb, T.M., 1999. *NHEMATIS: Project overview and future framework.* A report prepared by Nobility Environmental Software Systems Inc., Vancouver, B.C. for Emergency Preparedness Canada. 23 pp.

Webb, T. M., Sharpe, A., Hoffman, T., LaMorte, J. and Waterman, J., 1999. *NHEMATIS: A Natural Hazards Planning and Assessment Tool – Technical Report for Version 0.4.* A report prepared by Nobility Environmental Software Systems Inc., Vancouver, BC for Emergency Preparedness Canada. 41 pp.

Webb, T.M., 2000a. *NHEMATIS Version 1.3 - Demonstration Edition.* A report prepared by Lookfar Solutions Inc. for Emergency Preparedness Canada. 33 pp.

Webb, T.M., 2000b. *A review of strong motion attenuation equations and their applicability to earthquake damage prediction in Canada using NHEMATIS.* A report prepared by Lookfar Solutions Inc. for Emergency Preparedness Canada. 51 pp.

Canadian Subaerial Channelized Debris Flows: Past, Present, Future

Douglas F. VanDine
VanDine Geological Engineering Limited
267 Wildwood Avenue, Victoria, BC, V8S 3W2
Email: *vandine@islandnet.com*

and

Michael J. Bovis
University of British Columbia, Department of Geography
1984 West Mall, Vancouver, BC, V6T 1Z2
Email : *mbovis@geog.ubc.ca*

Introduction

Subaerial channelized debris flows (or simply "debris flows") are a type of landslide that involve water saturated, predominantly coarse-grained inorganic and organic material flowing rapidly down a steep, subaerial, confined pre-existing channel. In Canada, in the past, this phenomenon has also been referred to as "debris torrents" and "alpine mudflows". By their nature, debris flows are restricted to certain regions of Canada. They can vary in magnitude from less than 100 m^3 to several hundreds of thousands of cubic metres, and many have had a sizeable negative affect on resources, public and private property, and human life.

Prior to 1980 only a relatively few papers relating to Canadian debris flows had been published. In the early 1980s, a flurry of debris flows that occurred in southwestern British Columbia resulted in several millions dollars in property damage and a number of deaths. As a result, debris flows attracted the attention of the public, government agencies, design engineers and researchers. Over the past 20 years there has been a great deal of research associated with all aspects of Canadian debris flows – from initiation though to mitigation.

In preparation for this paper, a bibliography of papers, reports and theses associated with Canadian debris flows was compiled with the help of a workshop held at the University of British Columbia in April 2000. The bibliography forms an integral part of this paper. In addition to be bibliography, the workshop identified current debris flow research activity, and solicited and discussed future research needs. Therefore, although this paper is authored by only two individuals, many contributed to its content.

Bibliography

The "Canadian subaerial channelized debris flow" bibliography contains a few less than 300 citations. The word "subaerial" has deliberately been inserted into the title because there is a significant number of Canadian citations relating to "subaqueous" debris flows, which are beyond the scope of this paper and bibliography. It is recognized that probably not all documents relating to subaerial debris flows are captured in this bibliography. It is also recognized that bibliographies become out-of-date as soon as they are published. In spite of these limitations, we believe this bibliography provides a good snapshot of our present knowledge of Canadian subaerial channelized debris flows.

In addition to an alphabetical listing, the citations in the bibliography are cross-referenced into one or more of the following subcategories:

- General papers and review papers
- Regional studies and reports
- Single debris flow and creek studies and reports
- Geographical area
- Conditions for initiation
- Frequency and magnitude
- Transportation and deposition
- Rheology
- Debris fans and sedimentology
- Runout
- Study methodology
- Mitigation
- Theses
- Consulting and government reports
- Forestry-related studies and reports
- Field guides
- Debris flows mentioned in regional or general landslide studies and reports

Although most individual and regional debris flow studies have focussed on British Columbia, debris flows have also been documented in Alberta, Quebec, Newfoundland, and the Yukon. Regional studies have been carried out in all the above jurisdictions except Newfoundland.

The first reference to debris flows in Canada, published in 1942, was associated with "mudflows" in southern Yukon. A report on a train derailment by a "mudslide" near Revelstoke, BC in 1961 is probably the first debris flow-related case history and consulting report in Canada. The first well-documented Canadian debris flow, referred to as an "alpine mudflow", occurred in 1962 on Hell's Creek in Alberta. As the awareness of the phenomenon slowly grew, little by little so did the knowledge of the processes involved and the methods of mitigation. The first paper relating to debris flow mitigation described the method used to protect the residents of Port Alice on Vancouver Island in the mid-1970s.

The 1980s and 1990s have seen a dramatic growth in both the number of debris flow related studies, reports and papers, and the range in the topics covered. This is due in part to the fact that numerous debris flows occurred both in western Canada and the neighbouring US states in the early 1980s. And due in part because pure and applied research, and mitigation, naturally follow closely behind the development of awareness of any phenomenon, especially one that affects, or has the potential to affect, resources, property and human life.

Research in the past several years has begun to more systematically analyze and predict natural and Man-accelerated conditions for debris flow initiation, frequency/magnitude relationships and runout, to further investigate rheological models, and to develop different, and possibly better, methods of studying debris flows. One sign of the growth of debris flows as a relevant topic of research is the fact that approximately 10% of the citations in the bibliography are graduate theses.

Future Research

By looking back only a relatively few decades, the development of the Canadian debris flow knowledge base can easily be summarized. From the April 2000 workshop, we have a good idea of what aspects of debris flows are currently being studied in Canada. With assistance from the participants of the April 2000 workshop, the following topics have been identified as some areas where future debris flow research should be focused. These topics are listed in no particular order of priority.

- Basin characteristics and terrain attributes, and their relationship with debris flow activity (frequency and magnitude)
- Recharge rates of debris into the channels, and the relationship to frequency and magnitude
- Rainfall and rain-on-snow thresholds for debris flow initiation, and the relationship with factors such as antecedent conditions, geographical area and elevation
- Effects of climatic shifts, past and future, on debris flow activity
- Scour potential of debris flows in different geological environments and of different geological materials, and the relationships to magnitude and downstream affects
- Runout analyses and prediction, ranging from qualitative geomorphic methods to rheological and computer analyses

- Fan behaviour including methods for assessing the potentials of avulsion and incision of channels on the fan.
- Impacts downstream of the fan, including sediment routing and the related, and little understood, topic of debris floods
- Establishment of a systematic, consistent and on-going data base for cataloguing past and future debris flow events
- Testing both accepted, present-day and new, innovative mitigative measures and design philosophies, both in the laboratory and in the field
- Education of the public so that the phenomenon and the limitations of professional predictive techniques become better understood.

Closure

Our knowledge of Canadian subaerial channelized debris flows has come a long way in the past several decades. This is an exciting area of research, the results of which can have a substantial affect on future resource development, and on the protection of property and human lives.

Analysis of Post-Failure Slope Movements

Jean Vaunat
Departamento de Ingeniería del Terreno, Cartográfica y Geofísica
Universidad Politécnica de Cataluña
Módulo D2, c/ Jordi Girona, 1-3, 08034 Barcelona, Spain
Email : *jean.vaunat@upc.es*

and

Serge Leroueil
Département de Génie civil, Université Laval
Ste-Foy, Québec, G1K 7P4
Email : *serge.leroueil@gci.ulaval.ca*

Introduction

Vaunat et al. (1994) and then Leroueil et al. (1996) proposed a Geotechnical Characterization of slope movements that can be schematized by a 3-D matrix having the following axes: types of movement; types of material; and the four stages of movement: pre-failure, failure, post-failure and reactivation. Also, for each relevant element of this 3-D matrix, there is a characterization sheet including: the controlling laws and parameters, the predisposition factors, the triggering or aggravating factors, the revealing factors and the consequences of the movement.

The paper focuses on the post-failure stage, which generally is the most destructive, and on the mobility index. It is shown that this latter index can be described as the product of sub-indices associated to failure, brittleness of the material, ability of the soil to develop pore pressures, geometry of the moving soil mass and characteristics of the terrain. It is also shown how these aspects can be incorporated into the Geotechnical characterization of slope movements. This seems to provide a rational basis for examining slope movements at the post-failure stage and assessing associated risks.

Mobility index

Just before failure, there is equilibrium between the external and internal forces inside the slope. At failure, the reaction of the supporting mass, integral of the stress vector along the failure surface, is then equal to the weight of the mass plus the possible external static and dynamic loads. At this precise moment, the slope has failed but does not move. If the external forces increase or the reaction decreases, either due to a decrease in cohesion, an increase in pore pressure or a reduction in friction angle, the solid mass involved in the landslide starts to slide with an initial acceleration. It stops when the kinetic energy becomes equal to zero, that is, when all the potential energy has been dissipated into internal deformation of the mass and friction along the sliding surface.

Scheidegger (1973), Hsü (1975) and Sassa (1988) proposed a simple model to represent the displacement of the solid mass after failure, often called *friction* or *sled* model. The landslide is represented by a mass concentrated at one point. The total vertical drop and the total horizontal travel distance of the mass are respectively noted H and L. The sliding resistance T obeys to the law: $\|T\| = \mu \|N\|$, where μ is the friction coefficient classically used in Solid Mechanics, N the normal force exerted by the concentrated mass on the sliding surface and $\|.\|$ the Euclidean norm. It is assumed that no energy is dissipated inside the mass. By equating the loss of potential energy ΔE_P to the energy dissipated by friction ΔE_D, it is straightforward that:

$$H / L = \|T\| / \|N\| = \mu . \qquad (1)$$

In case of a drained sliding contact along a discontinuity with the same material on both sides, μ is equal to the tangent of the friction angle ϕ' of the material.

Despite crude assumptions, this model suggests that the ratio H / L may be related to characteristics of the material, and more generally to the environment. Heim (1932) proposed a similar measure to characterize the run-out of rock avalanches. It is called the *reach angle* and is expressed by $\phi_m = atan(H_T / L_T)$ where H_T and L_T are respectively the vertical and horizontal distances from the head of the landslide source to the distal margin of the displaced mass. The reach angle is easily determined in the case of past movements having left clear morphological features. Moreover, it is appropriate for risk estimation, because L_T measures the total length of the zone affected by the event, including the failure zone, the travel zone and the deposition zone.

Equation (1) moreover indicates that the ratio $H / (L\ tan\phi')$ is representative of the sliding mechanism. $H / (L\ tan\phi') = 1$ evidences a landslide having moved in drained conditions on a surface of the same material and without obstacles. $H / (L\ tan\phi') \neq 1$ indicates deviation from this reference pattern. In that perspective, Scheidegger (1973) proposed to estimate the run-out of rock falls by the *excessive travel distance* $L_e = L_T\left(1 - H_T / L_T\ tan\left(\overline{\phi'_{rock}}\right)\right)$, where $\overline{\phi'_{rock}}$ is an average value of friction angles of several hard rocks and taken equal to $32°$. L_e should be close to 0 for the reference drained mechanism. Data compiled by Hsü (1975) indicate that L_e may be as high as 12 km in case of very large volumes. This fact highlights the importance of mechanisms different from drained sliding in slope movements.

Hereafter, the friction model, extended to the case of deformable masses, will be used to clarify the different mechanisms controlling the mobility of a landslide. The mobility will be measured by the ratio I, called *mobility index*. I is defined as $H_T/(L_T \tan\phi') = \tan\phi_m/\tan\phi'$, where H_T and L_T are the lengths defined by Heim (1932).

When the failed mass deforms, the volume V and the surface in contact with the underlying formation S changes with time. In that case, and considering that no energy is dissipated by the internal deformation of the moving material, it can be shown that equation (1) becomes:

$$H_G/L_G = \bar{\tau}_g/\bar{\sigma}_{ng} \tag{2}$$

where H_G and L_G are the vertical and horizontal distances between the centers of gravity of the mass before and after the movement, $\bar{\tau}_g$ is the average shear strength during the movement and $\bar{\sigma}_{ng}$ the norm of the average normal total stress vector during the movement. $\bar{\tau}_g$ and $\bar{\sigma}_{ng}$ are obtained by averaging the strength τ_g and the stress vector σ_n, first over the surface S, and then over the duration of the post-failure movement.

The mobility index reads:

$$\begin{aligned} I = H_T/(L_T \tan\phi') &= H_G/(L_G \tan\phi')\cdot H_T L_G/H_G L_T = \bar{\tau}_g/(\bar{\sigma}_{ng}\tan\phi')\cdot H_T L_G/H_G L_T \\ &= \bar{\tau}_g/(\bar{\sigma}'_{nf}\tan\phi')\cdot \bar{\sigma}'_{nf}/\bar{\sigma}_{nf}\cdot \bar{\sigma}_{nf}/\bar{\sigma}_{ng}\cdot H_T L_G/H_G L_T \\ &= I_M\cdot I_F\cdot I_E\cdot I_{geo} \end{aligned} \tag{3}$$

where $\bar{\sigma}_{nf}$ and $\bar{\sigma}'_{nf}$ are respectively the average normal total stress and the average normal effective stress at failure.

$I_M = \bar{\tau}_g/(\bar{\sigma}'_{nf}\tan\phi')$ is called the *mechanical index*. Before failure, due to strain softening and progressive failure, the local stress conditions move from the peak strength envelope towards the critical state of the soil. At the onset of global failure, the average strength is thus between the peak strength and the large strain strength. Tavenas & Leroueil (1981) came to the conclusion that the strength parameters mobilized in a first-time failure are characterized by the friction angle ϕ' at large strain and an empirical cohesion, which takes into account strain rate effects and strength envelope curvature. By neglecting the cohesive component, $\bar{\sigma}'_{nf}\tan(\phi')$ appears to be the average strength at failure, $\bar{\tau}_f$. Since $\bar{\tau}_g$ is equal to the post-failure average shear strength, I_M links the mobility of the mass to the change in shear strength during motion. Pore pressure variations, destructuration, softening, particle reorientation, crushing and strain rate effects are the main mechanisms influencing I_M. While the first mechanism is controlled by consolidation process around the sliding surface, the others are reflected in the brittleness of the material. These effects can be separated by splitting I_M into:

$$I_M = \bar{\tau}_g/\bar{\tau}_{g0}\cdot\bar{\tau}_{g0}/(\bar{\sigma}'_{nf}\tan\phi') = I_C\cdot I_U \tag{4}$$

where $\bar{\tau}_{g0}$ is the average shear strength after all destructuration effects. Since these effects occur mostly in undrained conditions, the ratio $I_U = \bar{\tau}_{g0} / \left(\bar{\sigma}'_{nf} \ tan\phi'\right)$ is called *undrained index.* $I_C = \bar{\tau}_g / \bar{\tau}_{g0}$ accounts for the variation of shear strength due to subsequent changes in pore pressure and is called *consolidation index.*

$I_F = \bar{\sigma}'_{nf} / \bar{\sigma}_{nf}$ is related to the stress conditions at failure and is called *failure index.*

$I_E = \bar{\sigma}_{nf} / \bar{\sigma}_{ng}$ is called *elongation index.* In fact, it can be shown by integrating the stress equilibrium over the volume of the slide at failure that $\bar{\sigma}_{nf} = M_f \ g / S_f$, where M_f is the mass at failure, S_f the area of the failure surface and g the gravity. Similarly, $\bar{\sigma}_{ng} = \overline{M}_g \ g / \overline{S}_g$, where $\overline{M}_g$ is the average mass and $\overline{S}_g$ the average area of the sliding surface during movement. I_E represents the effect of changes in mass and area of contact.

$I_{geo} = H_G L_T / H_T L_G$ is the *geometrical index.* It corrects the lengths measured between the centers of gravity to the lengths L_T and H_T, suitable for risk estimation. It is related to the initial and final shape of the mass and to the travel distance.

The five indices I_U, I_C, I_F, I_E and I_{geo} describe the respective influence of material brittleness after failure, consolidation during movement, pore pressure at failure, elongation of the mass during movement and spatial distribution of the mass around the center of gravity, on the mobility of a landslide without obstacles. They have to be completed by a sixth index, the *field index* I_{field} which takes into account the effect of obstacles on the movement. When I_{field} is greater than 1, the mobility is reduced by the presence of obstacles; when it is less than 1, the mobility is increased by the characteristics of the supporting surface (for instance, low friction when the surface is a glacier).

Post-failure characterization

The indices previously defined are qualitative measures of the mechanisms that control landslide mobility. In the framework of the Geotechnical Characterization, each mechanism can be associated to a set of predisposition, triggering (or aggravating) and revealing factors. In the following text, the main relevant post-failure factors associated to each index are presented, as well as some guidelines for determining their values.

I_U measures the relative importance of post-failure strength change mechanisms (collapse, destructuration, reorientation, crushing, etc.) on mobility. It generalizes the brittleness index I_B initially proposed by Bishop (1967). I_U values strongly depend on the type of material. The Geotechnical Characterization considers the following main groups: hard intact rocks, hard fissured rocks, soft rocks, structurally complex formations, stiff clays, post-glacial clays, silts and fine sands, debris and coarse materials, truly collapsible soils (loess, ...) and other unsaturated materials (residual soils, ...). For each group, the way to estimate I_U will be different, because of the different mechanisms of strength loss. Evaluation of I_U will be illustrated on two types of materials: silts and fine sands, and stiff clays. In silts and fine uncemented sands, $\bar{\tau}_{g0}$ is the strength at the critical state for the void ratio reached at failure e_f, while $\bar{\tau}_f$ depends on the density of the soil. If the material is dilatant (stress conditions at failure and e_f below the critical state line CSL), $\bar{\tau}_f$ is slightly higher than the strength at the critical state. In that case, I_U is generally close to 1. If the material is contractant (state conditions above the CSL), the slope may fail with stress conditions below the failure criterion. A significant loss in strength is then observed, controlled by the distance to critical state conditions corresponding to e_f. In this case, an approximated value for I_U is $e^{-\psi/\lambda}$, where ψ is the state parameter defined by Been & Jefferies (1985) and λ the slope of the CSL. The factors related to the compacity of the material, the stress state at failure and the position and slope of the CSL are post-failure factors for this type of material. The highest value between 1 and $e^{-\psi/\lambda}$ expresses numerically the contribution of each of these factors to the overall mobility. In stiff clays, the mechanism of strength loss is related to particle reorientation. In these materials, $\bar{\tau}_{g0}$ is the residual strength, while $\bar{\tau}_f$ is often close to the strength at the critical state. With the assumption that there is no significant pore pressure change during the transition between the critical state and the residual state as a result of the small thickness of the shear band, I_U can be approximated by the ratio $tg\phi' / tg\phi_r$ where ϕ' is the friction angle of the normally consolidated clay and ϕ_r the residual friction angle. Classical relationships between these angles and plasticity index I_P or clay fraction CF provide crude estimations of I_U. Using correlations with I_P, I_U appears to vary between 1 for I_P values less than 25 to about 0.2 for I_P values greater than 100. Plasticity of the clay is thus an important predisposition factor for stiff clays.

I_C is an indicator of the contribution of pore pressure change mechanism along the sliding surface during movement. Pore pressure changes can occur either inside the mass (Hutchinson & Bandhari, 1971; Hutchinson, 1986; Picarelli, 1988; among others) or in the supporting layer (Sassa, 1988). The sliding-consolidation model proposed by Hutchinson (1986) gives a tool to assess the value of I_C, which depends mainly on the coefficient of consolidation of the colluvium, the drainage length inside the sliding mass, the coefficient of consolidation of the supporting material and the drainage conditions of the terrain underlying the slide. Also, the velocity of the movement gives possibilities to generate pore pressure by dynamic effects. All factors related to these phenomena characterize I_C.

The failure index I_F can be written as $1 - R_{uf}$, where R_{uf} is the ratio of the average pore pressure along the failure surface $\bar{u}_f$ divided by $\bar{\sigma}_{nf}$. It comes out that the distribution of pore pressure at failure influences the mobility of the mass; this has in particular been evidenced by Hutchinson (1986), who showed a strong dependency of the back-analyzed travel distance of Aberfan debris flow the pore pressures considered at failure. Since $\bar{\sigma}_{nf} = M_f \, g / S_f$, the factors associated to I_F are the solid mass at failure, the area of the failure surface and pore pressure distribution at failure. Their contribution to mobility is given by $1 - R_{uf}$.

The elongation index I_E weighs up the contribution of mass changes and deformation on mobility. When there is no deposition or erosion, the solid mass remains constant. Assuming a linear variation of the contact area with time, I_E can be approximated by $(S_f + S_{ge}) / (2S_f)$, where S_{ge} is the contact area at the end of the movement. On the opposite, if the contact surface does not change significantly, I_E reflects the loss or gain in mass. In all cases, the prediction of I_E value is complex and generally requires the integration of the equations of movement for a deformable mass. Factors such as mass deformability, related to the degree of remolding of the material, geometry of the supporting surface and direction of the movement with respect to the steepest slope gradient controls the value of I_E. Qualitatively, I_E depends on the type of movement in a given environment and has to be assessed on a regional basis.

The geometrical index I_{geo} takes into account the effect of the spatial distribution of the mass around the center of gravity. The remarks made for the elongation index apply to I_{geo}, which also has to be assessed on a regional basis.

The value of the field index I_{field} depends mainly on the characteristics of the surface below the slope (scree deposit, grass, forest, etc.). In the framework of risk mapping, Corominas (1990) developed a technique, which provides an approach for assessing the value of the field index. It consists in defining zones of isomobility in the plot: reach angle vs. volume of mass for distinct types of surface and for similar movements. Assuming that indices I_U, I_C, I_F, I_E, and I_{geo} do not vary too much from one movement to the other, broad ranges of I_{field} can be deduced for the considered regional environment.

As a conclusion, it can be said that defining the mobility of landslides is difficult. It is however thought that the approach proposed here provides a rational for interpreting and classifying the factors which are controlling the mobility of landslides, and thus for assessing the associated risk which is strongly related to the travel distance of the failed mass.

Bibliography

Been, K. & Jefferies, M.G. 1985. A state parameter for sands. *Géotechnique*, vol. 35, pp. 99-112.

Bishop, A.W. 1967. Progressive failure with special reference to the mechanism causing it. *Geotech. Conf. On Shear Strength Properties of Natural Soils and Rocks*, Oslo, Norway, vol. 2, pp. 142-150.

Corominas, J. 1990. Risk mapping in the Pyrénées area: a case study. *Proc. of the Symp. of Hydrology in Mountainous Regions*, Lausanne, Switzerland, IAHS Publ. No. 194, pp. 425-428.

Heim, A. 1932. Bergstürz und Menschenleben, Fretz und Wasmuth. (English translation by Skermer, N.A. 1989. Landslides and human lives. BiTech Publishers, Vancouver, B.C.).

Hsü, K.J. 1975. Catastrophic debris streams generated by rockfalls. *Geol. Soc. of Am. Bull.*, vol. 86, pp. 129-140.

Hutchinson, J.N. & Bhandari, R.K. 1971. Undrained loading, a fundamental mechanism of mudflows and other mass movements. *Géotechnique*, vol. 21, pp. 353-358.

Hutchinson, J.N. 1986. A sliding-consolidation model for flow slides. *Can. Geotech. J.*, vol. 23, pp. 115-126.

Leroueil, S., Vaunat, J. Picarelli, L., Locat, J., Lee, H. & Faure, R.M. 1996. Geotechnical characterization of slope movements. *Proc. of 7th Int. Symp. on Landslides,* Trondheim, Norway, vol. 1, pp.53-74.

Picarelli, L. 1988. Modellazione e monitoraggio di una colata in formazioni strutturalmente complesa. *Proc. of the Symp. "Cartografia e monitoraggio dei movimienti franosi"*, Bologna, Italy, pp. 119-130.

Sassa, K. 1988. Special lecture: Geotechnical model for the motion of landslides. *Proc. of 5th Symp. on Landslides,* Lausanne, Switzerland, vol. 1, pp. 37-55.

Scheidegger, A.E: 1973. On the prediction of the reach and velocity of catastrophic landslides. *Rock Mechanics*, vol. 5, pp.231-236

Tavenas, F & Leroueil, S. 1981. Creep and failure of slopes in clays. *Can. Geotech. J.*, vol. 8, pp. 106-120.

Vaunat, J., Leroueil, S. & Faure, R.M. 1994. Slope movements: a geotechnical perspective. *Proc. of 7th Int. Congress Int. Assoc. of Engineering Geology,* Lisbon, Portugal, vol. 3, pp.1637-1646.