EVOLUTION OF LANDSLIDE HAZARD AND RISK ASSESSMENTS IN CANADA

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ABSTRACT
Justice Thomas Berger's 1973 British Columbia (BC) Supreme Court decision is arguably the first landslide risk-based ruling in Canada. It halted a proposed 126-lot residential development near Rubble Creek, BC, because of the probability that a catastrophic landslide could affect the development,. Since then, landslide hazard and risk assessments have evolved in BC and, to varying degrees, in other Canadian provinces. This has been in concert with the evolution of the science and engineering of landslide hazard and risk assessments worldwide. Currently, in some ways, Canada is leading the way. Canada has two of the three jurisdictions in the world that have adopted legally binding quantitative tolerable and acceptable landslide risk criteria: the District of North Vancouver, BC and the Town of Canmore, AB.

Une décision prise en 1973 par le juge Thomas Berger de la Cour suprême Colombie-Britannique (C-B) est vraisemblablement la première décision fondée sur des règles reliées au risque de glissement de terrain au Canada. Elle a arrêté un projet d'aménagement résidentiel de 126 lots près du Rubble Creek, C-B, Cette décision était en raison d'un haut taux de probabilité qu'un glissement de terrain catastrophique pourrait affecter le développement. Depuis, les aléas et les évaluations de risque dus aux glissements de terrain ont évolué en C-B et, à différents degrés dans les autres provinces canadiennes. Cela a suivi l'évolution de la science et de l'ingénierie des aléas et des évaluations de risques dus aux glissements de terrain à travers le monde entier. Actuellement, à certains égards, le Canada est le chef de file car il possède deux des trois communautés au monde qui ont adopté des lois reliées aux critères de risque quantitatifs tolérable et acceptable pour les glissements de terrain, soient: le district de North Vancouver, C-B et la ville de Canmore, AB.

1. INTRODUCTION

It is thought that the first systematic or scientific studies of landslides were carried out in Europe. In the introduction to the [US] Transportation Research Board, Special Report 247, *Landslides: Investigation and Mitigation*, Turner and Jayaprakash (1996) briefly describe studies of the 1806 Rossburg landslide (Switzerland), the 1839 Bindon landslide (England) and the 1881 Elm landslide (Switzerland). These authors also briefly describe the work of French canal engineer, Alexandre Collin, and refer to his 1846 publication on the stability of clay slopes (Collin 1846)[1]. Collin's work may be the first geotechnical slope stability analysis.

Some of the first slope stability studies in Canada were associated with rock slides along Champlain Street in Québec City, QC, in the late 1800s (Baillargé 1889 and 1893, as reported in Locat 2016), late 1800s glaciolacustrine silt slides along the South Thompson River, BC (Stanton 1898), Champlain Sea clay slides along the Liévre River, QC, in the early 1900s (Ells 1904 and 1908) and the 1903 rock avalanche at Frank, AB (McConnell and Brock 1904). The first two studies were carried out by civil engineers; the latter two by geologists.

For the next 125 years or so after Collin's 1846 publication, the stability of natural and engineered slopes was typically analysed using factors of safety: the ratio of shear strength divided by shear stress. This method of analysis is now referred to as limit equilibrium analysis because, for failure to occur, the soil or rock has to reach its limit of stability along a specific, or critical, slip surface.

With the advent of computers in the 1960s and 1970s, limit equilibrium analyses have become more sophisticated and other methods of predicting slope failure have been, and continue to be, developed; for example slope displacement analysis, slope deformation analysis and probabilistic methods. In parallel, methods have been, and continue to be, developed to estimate landslide runout. Many of these developments, some of which have been pioneered by Canadians, are summarized by Lato et al. (2016).

The limit equilibrium, slope displacement, slope deformation and probabilistic methods are well suited to a single, natural or engineered slope, for which the geotechnical properties and parameters are well known or can be obtained by site investigation and laboratory testing.

This paper, however, emphasizes an analytical method that is better suited to the management of the stability and safety of slopes on a broader geographical scale. It summarizes the evolution of landslide hazard and risk assessment in Canada. Landslide hazard and risk assessment involves estimating the probability or likelihood of landslides occurring, estimating the consequences (in the case of risk), and comparing the results with tolerable or acceptable hazard or risk criteria. Although pan-Canadian in scope, this paper emphasizes western Canada, in part, because of this author's experience.

[1] In the mid-1900s, Robert Legget (National Research Council of Canada) facilitated the translation of Collin (1846) into English (Schriever 1956).

The evolution of knowledge typically has a number of stages (paraphrasing from Meier (2000)):

- arouse interest in the new knowledge (discover and see the benefits of learning about);
- encounter the new knowledge in meaningful ways;
- integrate the new knowledge with existing knowledge; and
- apply the new knowledge.

This paper is organized following the above stages.

There is typically a time lag between when a discovery is made, or when work is carried out, publication of that discovery or work, and adoption of best and/or standard practices. Therefore, some of the dates provided herein, except for publication dates, are estimates.

Although this author has been careful not to confuse the now accepted landslide hazard and risk terms 'analysis' and 'assessment', the authors of some of the referenced papers, especially the earlier publications, may not have made this distinction.

2. TERMINOLOGY

It is assumed that most readers are somewhat familiar with landslide hazard and risk assessment terminology, and this paper will only define a few terms.

In its simplest form risk (*R*) is the product of probability or likelihood of landslide occurrence (*P*) and consequence (*C*), or $R = P \times C$. The probability or likelihood of a landslide occurring is sometimes referred to as hazard.

In a more complex, but more realistic and practical form, risk is the product of five components, shown in Table 1. Combining these five components, $R = P(H) \times P(S{:}H) \times P(T{:}S) \times V \times E$.

Table 1. Components of risk.

Component	Description
P(H), probability of occurrence	Probability or likelihood of a landslide (hazardous event) occurring
P(S:H), spatial probability	Probability of a landslide affecting a specific location? Considers where a landslide will travel or regress to
P(T:S), temporal probability	If an element at risk is mobile, probability it will be at that specific location when the landslide occurs. If an element at risk is not mobile, *P(T:S)* = 1
V, vulnerability	If the element at risk is at that specific location at the time of the landslide, its vulnerability depends its type and character, its robustness (or fragility) and its exposure to (protection from) the landslide. If total loss is assumed, *V* = 1
E, number of individuals at risk	*E* = 1 for individual risk

Partial risk, also referred to as encounter probability, is the combination of *P(H)* and *P(S:H),* the consequence of the landslide affecting a specific location.

Individual risk is related to the safety of individuals, typically those most at risk; societal risk is related to the safety of a group of individuals integrated over all hazard scenarios considered.

Tolerable risk is risk that society is willing to live with to achieve some benefit, but which may require some form of risk reduction; acceptable risk is risk that society is prepared to accept without further consideration.

Figure 1 summarizes the landslide risk management process as adapted from ISO (2009) in VanDine (2012).

The double outlined boxes in Figure 1 indicate that risk assessment is a combination of risk identification, risk analysis and risk evaluation. A landslide hazard analysis or assessment does not consider the consequences.

Landslide hazard and risk assessment terminology is described in more detail in Wise et al. 2004 and VanDine 2012.

3. 1965-1985: AROUSING INTEREST

Although not in Canada, in 1965, Dr. Arthur Casagrade (Harvard University), wrote a paper entitled *Rule of the calculated risk in earthwork and foundation engineering* (Casagrade 1965). This paper introduces *"the nature of risk and the need to balance safety with economy in geotechnical design"* (Wu et al. 1996). Although the concept of risk was being used in the business and management fields much earlier, this 1965 paper is considered to be the spark that aroused interest in risk in the geotechnical field, including slope stability.

3.1 BC Land Registry and Land Titles Acts

In Canada in the early 1970s, the British Columbia (BC) *Land Registry Act* (Section 96) stated: *"In considering an application before him for subdivision approval [outside of a municipality], the [BC Ministry of Transportation and Infrastructure; BC MOTI*[2]*] approving officer … may refuse to approve the subdivision if in his opinion the anticipated development of the subdivision would injuriously affect the established amenities of adjoining or adjacent properties or would be against the public interest."*

Based upon the above, in 1972, a proposed 126-lot subdivision near Rubble Creek, north of Squamish, BC, was not approved because it could potentially be affected by another very large rock avalanche, such as occurred in 1855. The developer appealed the decision to the BC Supreme Court, however, it was upheld by Justice Thomas Berger.

After hearing evidence from expert engineers and geologists, Justice Berger ruled that there was sufficient likelihood of a catastrophic landslide occurring and affecting the community (Berger 1973). By 'catastrophic', he referred to a very large landslide that could potentially

[2] Over the years, the BC MOTI has gone through several name changes. This paper refers to this ministry by its current name.

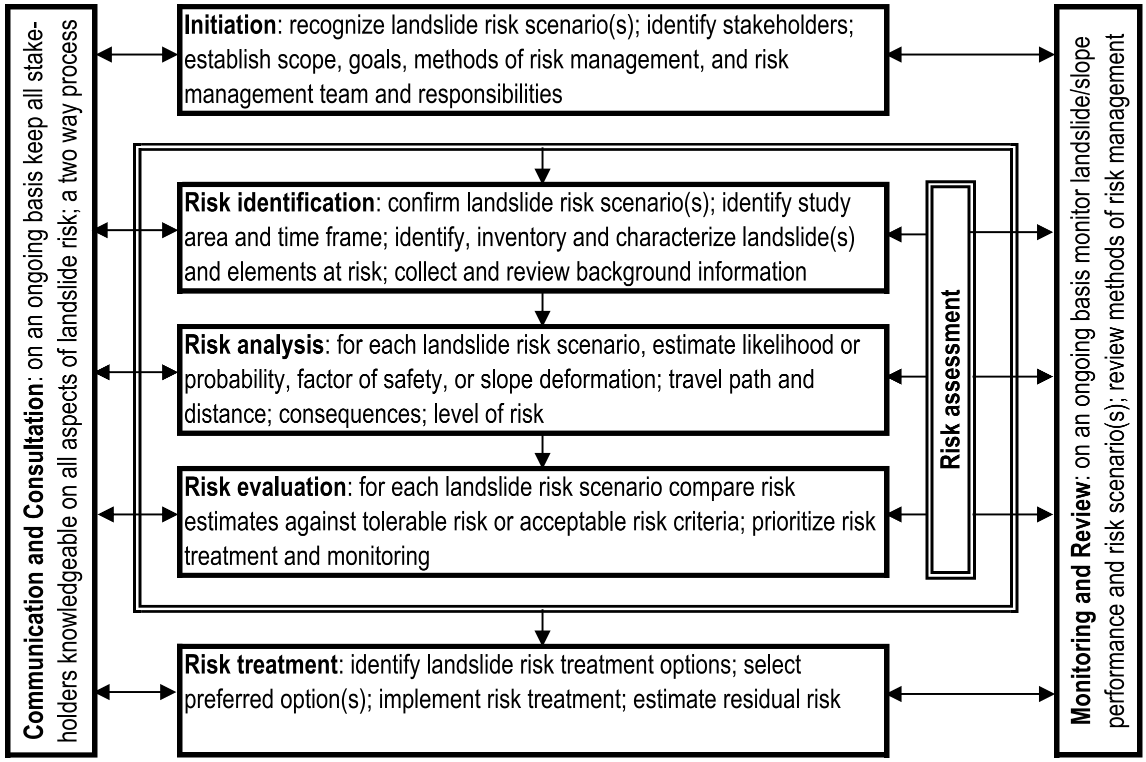

Figure 1: Landslide risk management process adapted from ISO (2009) in VanDine (2012).

affect more than 100 residences and potentially result in the loss of many lives. In his ruling, Justice Berger states that: *"Dr. Mathews* [University of British Columbia] *and Mr. Naismith* [sic, Mr. Nasmith of Thurber Engineering Ltd.] *both calculate the risk of a slide on a time scale of thousands of years. They say there is a probability of a* [catastrophic] *slide at the Barrier in the next 10,000 years. It may occur next year, it may occur in a thousand years, it may occur in 10,000 years. Yet for both of them the risk is real enough that neither would want to live in the subdivision."* This has been interpreted as an annual probability of occurrence of 1:1:10,000 (0.5% probability in 50 years), although Justice Berger did not specify this probability. Because this ruling involves a probability of landslide occurrence and the associated unacceptable consequences, it is considered to be the first landslide risk-based ruling in Canada.

Subsequent to this ruling, the BC MOTI began to provide geotechnical assistance to approving officers. The geotechnical staff, primarily geologists, investigated selected proposed subdivisions for the risk from landslides, among other natural hazards (VanDine and Lister 2011). Later in the 1970s, this assistance expanded to the BC MOTI geotechnical staff carrying out regional slope stability mapping for selected areas of proposed residential development; for example, the South Thompson and South Columbia valleys (Buchanan 1977 and Haughton 1978).

In 1979, the BC *Land Registry Act* was replaced by the BC *Land Titles Act*. Section 86 of the latter contains provisions for *"refusing to approve"* a subdivision *"if the Approving Officer considers the land is subject, or could reasonably be expected to be subject, to flooding, [soil] erosion, land slip [landslide] or [snow] avalanche"*. The approving officer may also require a report *"certifying"* that *"the land may be used safely for the use intended"* and/or recommending one or more registered covenants restricting the use of the land. The phrase *"safely for the use intended"* was not further defined.

In the early 1980s, the BC MOTI decided it was more appropriate for such reports to be prepared by qualified consultants retained by subdivision applicants. To provide guidance, the BC MOTI reviewed what should be considered acceptable hazard or risk criteria. At the time, the National Building Code of Canada (NBCC 1985) referred to an earthquake probability of 10% in 50 years for ground motions for seismic building design to minimize loss of life and, therefore, the BC MOTI asked geotechnical professionals to *"think in terms of a 10% probability in 50 years"* (an annual probability of 1:475) of a landslide occurring and affecting the safety of the intended use (VanDine and Lister 2011). This guidance was first codified in 1993 (BC MOTI 1993). (If *P(H)* x *P(S:H)* is considered to be partial risk, this guidance is related to acceptable risk criteria; if *P(H)* x *P(S:H)* is considered as encounter probability, this guidance is related to acceptable hazard criteria.)

3.2 BC Terrain and Terrain Stability Mapping

In 1976, in parallel to the BC subdivision approval process, the BC Ministry of Environment (BC MOE) adapted and adopted an airphoto-based terrain mapping and classification system developed by the Geological Survey of Canada (BC ELUCS 1976, Howes and Kenk 1988 updated in 1997). The system, which divides the terrain into polygons with similar geomorphology, is typically applied to map scales between 1:20,000 to 1:50,000 (BC Resource Inventory Committee (BC RIC) 1996a).

In 1978, the forest company MacMillian Bloedel Ltd. extended the BC terrain mapping and classification system to include derivative terrain stability mapping of its BC coastal forest lands (Bourgeois 1978). The terrain stability mapping adds, somewhat subjectively, one of five terrain stability classes to the polygons. The terrain stability classes are based to a large degree on slope topography and evidence of past instabilities, and provide a qualitative estimate of likelihood of occurrence and in general terms where existing and/or future development could be affected by landslides and where future development could reduce slope stability. Subsequently this terrain stability mapping system was adopted by other BC forest companies, the BC Ministry of Forests (BC MOF), and adapted to other types of land use, development and linear project planning in BC (Chatwin et al. 1991 updated in 1994, BC MOF 1995 updated in 1999, and BC RIC 1996b). Table 2 is an example of what is known as the '5-Class System' for the forest industry.

BC's terrain stability mapping is an example of landslide susceptibility (or probability, or hazard) mapping that can be extended into landslide risk mapping. In the 1970s and early 1980s, these types of landslide hazard and risk maps were being developed, introduced and used in many parts of the world. In 1984, Dr. David Varnes (US Geological Survey) and the International Association on Engineering Geology's Commission on Landslides and Other Mass Movements on Slopes summarized the state-of-the-art of this mapping. The resulting publication entitled *Landslide Hazard Zonation: a review of principles and practice* was published by UNESCO (Varnes et al. 1984).

3.3 Ontario, Québec and Alberta

BC's terrain and terrain stability mapping system has recently been reviewed in a national context by Jackson et al. (2012). With regards to the time period 1965-1985, Jackson et al. (2012) also refer to regional landslide hazard mapping being carried out in Ontario in the early to mid-1970s (Klugman and Chung 1976) and in Québec in the early 1980s (Lebuis et al. 1983).

In Alberta in the mid- to late 1970s, Dr J.S. Gardner (University of Calgary) estimated the frequency and magnitude of rockfalls and rockslides in the Kananaskis area, west of Calgary (Gardner 1980 and 1983). This research may be the first regional quantitative landslide analysis in Canada.

Table 2: Terrain stability classes for the BC forest industry, adapted from Chatwin et al. (1994).

Class	Description
I	No significant slope stability problems
II	No significant slope stability problems Conventional road construction and harvesting practices should not significantly reduce slope stability Periodic maintenance, including ditch clearing, to be expected due to sloughing along road cuts
III	Minor slope stability problems can develop Harvesting should not significantly reduce slope stability Low likelihood of post-harvesting slope failures Minor slumping expected along road cuts on slopes >30 degrees, especially 1-2 years following construction
IV	Expected to have areas with moderate to high likelihood of slope failures following conventional road construction Wet season road construction should significantly increase likelihood of slope failures Moderate likelihood of slope failures in harvested areas Field inspection by a PEng or PGeo should be made prior to any development to assess slope stability in detail
V	High likelihood of slope failures after conventional road construction or harvesting Field inspection by a PEng or PGeo should be made prior to any development to assess slope stability in detail

3.4 Sea-to-Sky Highway, BC

Between 1969 and 1983, a number of debris flows occurred along Highway 99 (the portion of that highway now known as the 'Sea-to-Sky Highway'). These events affected the highway, BC Rail (now CN Rail) and a number of coastal settlements located on creek fans, and resulted in 12 fatalities. In 1982, BC MOTI commissioned a debris flow and flood risk analysis of 26 creeks along the highway from North Vancouver to Britannia Beach. This study was carried out by Mr. Graham Morgan, Dr. Oldrich Hungr and this author of Thurber Engineering Ltd., and resulted in what may be the first regional qualitative landslide risk analysis in Canada (Thurber Engineering Ltd. 1983, Hungr et al. 1984 and VanDine 1985).

3.5 United States

It is interesting to note that the definitive [US] Transportation Research Board Special Report 176, *Landslides Analysis and Control* (Schuster and Krizek 1978)[3], published in 1978, makes no mention of landslide hazard and risk analysis or assessment.

[3] Schuster and Krizek (1978) was the successor of the [US] Highway Research Board Special Report 29 *Landslides and Engineering Practice* (Eckel 1958), and the predecessor of [US]

Towards the end of this time period, Robert Whitman (Massachusetts Institute of Technology) published a paper entitled *Evaluating calculated risk in geotechnical engineering* (Whitman 1984). Among other things the paper presented a graph of annual probability of failure causing damage versus lives lost and approximated costs. This graph, shown as Figure 2, is considered the first use of a F-N-type diagram in geotechnical engineering and, as discussed later, F-N diagrams will become an important element in the story of landslide risk assessments.

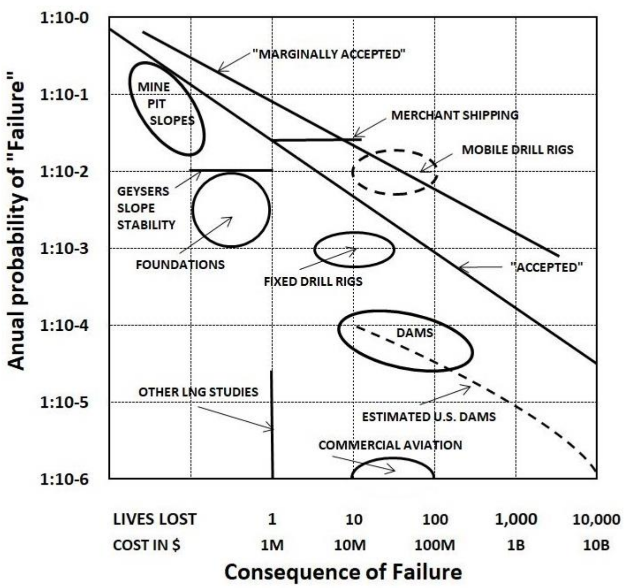

Figure 2: F-N-type diagram[4] adapted from Whitman (1984).

3.6 1965-1985 Summary

By the end of the period 1965-1985, interest in landslide hazard and risk identification and analysis had been aroused in Canada, and early qualitative and quantitative analyses had been carried out. However, except for Justice Berger's 1973 ruling, and the BC MOTI's guidance to *"think in terms of a 10% probability in 50 years",* tolerable or acceptable landside risk criteria had not been introduced.

4. 1985-1995: ENCOUNTERING NEW KNOWLEDGE

Several events in the mid- to late 1980s helped with the evolution of landslide hazard and risk assessments in Canada.

4.1 Mr. Graham Morgan, British Columbia

Following Thurber Engineering Ltd.'s qualitative risk analysis along BC's Sea-to-Sky Highway in the early 1980s (see Section 3.4), Mr. Morgan became further interested in the topic of landslide risk and its acceptance. His interest grew, especially after discussions with Dr. Niels Lind, a Danish-Canadian structural engineer and specialist in engineering reliability and risk analysis, and with a Thurber Engineering Ltd. colleague, Dr. Robert Pack (Morgan, personal communication).

In the period 1986-1988, Mr. Morgan and Dr. Pack, published several early papers on landslide risk; for example, *Philosophy of landslide risk evaluations and acceptance* (Pack et al. 1987). In a 1988 paper, they introduced the concept of involuntary versus voluntary risk to landslide assessments, and compared the probabilities of death from various activities (Pack and Morgan 1988).

4.2 The Cave Tables, British Columbia

In 1985, amendments to BC's *Municipal Act* (Sections 945, 976 and 734) required geotechnical investigations of, and reports for, buildings and land development *"for the protection of development from hazardous conditions"*. Therefore after 1985, considering the BC *Land Titles Act* (1979) and the 1985 amendments to BC *Municipal Act*, almost all residential development in potentially hazardous areas in BC required some form of landslide risk assessment. Although the demand was growing, tolerable or acceptable risk criteria were, at best, poorly defined; a situation affecting new residential development and those responsible for approving such development.

These concerns were expressed by Mr. Peter Cave and Mr. Hugh Sloan, land use planners of the Regional District of Fraser-Cheam (now known as the Fraser Valley Regional District, east of Vancouver, BC) and Mr. Robert Gerath of Thurber Engineering Ltd. in their 1990 paper *Slope hazard evaluations in southwest British Columbia* (Cave et al. 1990).

To address these concerns, Mr. Cave developed a series of tables that required geotechnical professionals to identify and characterize natural hazards (including landslides), and to qualitatively estimate the probability of occurrence and consequences based on the type of natural hazard, the type of proposed development and possible remedial or protective measures (Cave, 1992a and 1992b). The risk acceptability criteria were based on 1) the interpretation of Justice Berger's 1973 ruling of an unacceptable landslide return period of 10,000 years affecting a proposed subdivision; 2) the BC MOTI's guideline of 10% probability of occurrence in 50 years affecting the intended use, and 3) the 200-year return period used for the provincially sponsored flood-proofing program.

What have become known as the 'Cave Tables' were subsequently revised in 1993, adopted by the Fraser Valley Regional District and are still being used by that regional district. These semi-quantitative tables were the first acceptable landslide risk criteria adopted in Canada. Table 3 is an example of the Cave Table for major catastrophic landslides.

Transportation Research Board Special Report 247 *Landslides: Investigation and Mitigation* (Turner and Schuster 1996). It is this author's understanding that an update of Special Report 247 is currently being planned.

[4] Technically, Whitman's figure is a f-N diagram because the annual probability of failure is not cumulative, as is the case in F-N diagrams.

Table 3: An example 'Cave Table', for major catastrophic landslides, adapted from Cave (1992a updated in 1993).

MAJOR CATASTROPHIC LANDSLIDE	Range of Estimated Annual Probability of Occurrence				
Type of Development	>1:200	1:200 to 1:500	1:500 to 1:1000	1:1000 to 1:10,000	<1:10,000
Minor Repair (<25%)	5	2	1	1	1
Major Repair (>25%)	5	5	2	1	1
Reconstruction	5	5	5	1	1
Extension	5	5	5	1	1
New Building	5	5	5	1	1
Subdivision (infill/extend)	5	5	5	5	1
Rezoning (for new community)	5	5	5	5	5

Approval response numbers

1. Approval without conditions relating to hazards
2. Approval without siting or protective works conditions, but with a covenant including a "save harmless" clause
3. Approval with siting requirement to avoid the hazard, or with protective works requirement to mitigate the hazard
4. Approval as (3) above, but with a covenant including a "save harmless" clause, as well as siting conditions, protective works conditions, or both
5. Not approvable

Type of development

- Minor Repair: cost of repair or renovation < 25% of the value of the building before repair or renovation
- Major Repair: cost of repair or renovation >25% of the value of the building before repair or renovation
- Reconstruction: more complete form of Major Repair (>25%) and offers opportunity to relocate the building
- Extension: implies increased density of use and therefore a greater annual risk; and relocation is not an option
- New Building: construction of new residence on an existing vacant property
- Subdivision (infill/extend): legal subdivision of property, infilling or extension of existing residential development
- Rezoning (for new community): new community or amendment to community plan

4.3 Geological Hazards in British Columbia Workshop, Victoria, BC

In 1991, the BC Ministry of Energy Mines and Petroleum Resources, the BC MOE and the BC MOTI hosted the *Geological Hazards in British Columbia* workshop, in Victoria, BC. The proceedings, published in 1992, included the aforementioned paper by Cave (1992a), and a paper by Mr. Morgan (who by then was an independent consultant) entitled, *Quantification of risks from slope hazards* (Morgan 1992). This paper further discusses voluntary versus involuntary risks, further compares the probabilities of death from various activities, introduces a method for allocating probabilities to rarely occurring events such as landslides and, for the first time, introduces a F-N diagram for landslide risk acceptability (Figure 3).

4.4 GeoHazards 1, Vancouver, BC

In 1992, the Vancouver Geotechnical Society and the Canadian Geotechnical Society (CGS) held the *Geotechnique and Natural Hazards* symposium in Vancouver, BC[5]. Mr. Cave opened the symposium with a keynote address entitled, *Natural hazards, risk assessment and land use planning in British Columbia:*

[5] Although not referred to as such, this is considered to be 'GeoHazards 1'

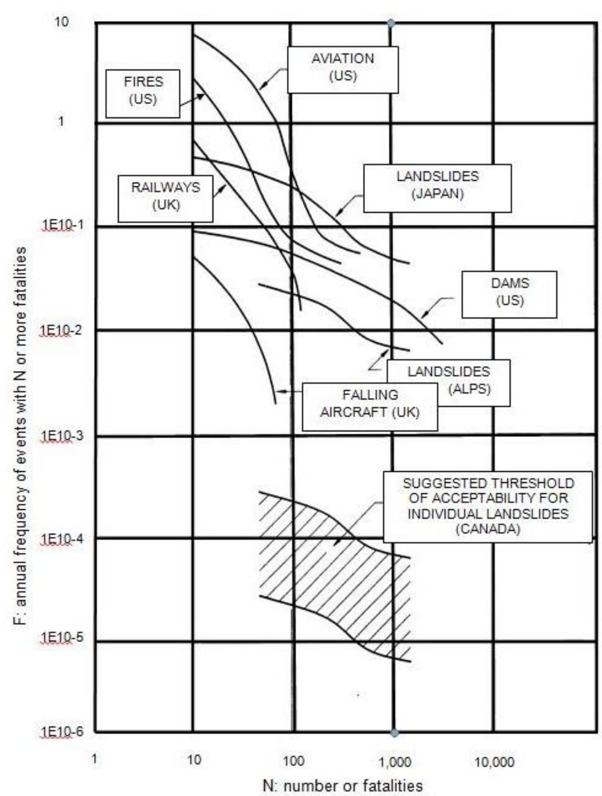

Figure 3: F-N diagram adapted from Morgan (1991).

progress and problems (Cave 1992b). Mr. Morgan and his co-authors contributed a paper on *Evaluating total risk to communities from large debris flows* in which, among other things, they introduce the concept of total risk, and present a quantitative risk analysis for Charles Creek, one of the 26 debris flow creeks along the Sea-to-Sky Highway investigated by Thurber Engineering Ltd. in the early 1980s (see Section 3.4) (Morgan et al. 1992).

The proceedings of this symposium (Imrie et al. 1992) contain a number of other relevant papers. One in particular is a paper from Québec entitled *Hazard and risk analysis of slope instability* (Vaunet et al. 1992). This paper discusses landslide hazard and risk analysis, and presents, as an example, a qualitative landslide hazard analysis for the 1975 St. Ambroise landslide in Québec.

4.5 Cheekye Fan, BC, Part 1

In the early 1990s, Thurber Engineering Ltd. and Golder Associates Ltd. jointly carried out a quantitative landslide risk analysis of the lower Cheekye Fan, north of Squamish, BC. They extended the 1970s and early 1980s studies by Crippen Engineering Ltd. The fan has the potential for a very large residential development (upwards of 750 lots), but is potentially subject to debris flows from the Cheekye River. Besides the unpublished joint report (Thurber Engineering Ltd.-Golder Associates Ltd. 1993), this work resulted in several papers that describe early quantitative landslide risk analyses (Hungr et al. 1993, Hungr and Rawlings 1995, and Sobkowitz et al. 1995).

4.6 Dr. Morgenstern; Dr Fell; University of Alberta

In 1992, Dr. Nobert Morgenstern (University of Alberta) presented a paper to the American Society of Civil Engineers entitled *The evaluation of slope stability–a 25 year perspective* (Morgenstern 1992). This presentation reviewed the developments in the topic since the ASCE's 1966 *Conference on Stability and Performance of Slopes and Embankments*. It is interesting that Morgenstern made no mention of landslide hazard and/or risk assessment in his paper…but that was to change.

In 1994, Dr. Robin Fell (University of New South Wales in Australia) published a seminal paper in the *Canadian Geotechnical Journal* simply entitled *Landslide risk assessment and acceptable risk* (Fell, 1994). Among other topics, the paper defines terms related to hazard and risk, discusses methods for quantifying risks, and discusses acceptable risk in relation to other risks accepted by the community. Approximately the same time, Dr. Fell spent a portion of his sabbatical at the University of Alberta with Dr. David Cruden and Dr. Morgenstern.

Also in 1994, Mr. Chris Bunce completed his MSc thesis at the University of Alberta on *Risk analysis for rock fall on highways* (Bunce 1994). This author considers this thesis, and the subsequent paper (Bunce et al. 1997) to be watershed contributions to quantitative landslide risk analysis and assessments in Canada.

In 1995, Dr. Morgenstern presented the 3rd Casagrande Lecture at the *10th Pan American Conference on Soil Mechanics and Foundation Engineering,* in Mexico. His topic was *Managing risk in geotechnical engineering* (Morgenstern 1995) in which he referred to the aforementioned paper by Casagrade (1965). Although the paper is not specific to landslides, many landslide examples are used. The lecture includes topics of uncertainly in quantified risk analysis, qualitative and quantitative risk, and acceptable risk.

In his paper Morgenstern states *"The important question asked of the geotechnical engineer is not whether a slope is safe or not, or what is the Factor of Safety; instead, the engineer is asked to assign return period probabilities to events of different magnitudes".* Prophetically, the paper continues, *"An enhanced understanding of risk management concepts, together with increased utilization of quantified risk assessment methods, are advocated in both the teaching and practice of Geotechnical Engineering"*. Morgenstern acknowledges that *"In Canada, Mr. [Graham] Morgan has led a risk-based approach to geohazard engineering"*.

4.7 Internationally

Internationally, during the period 1985-1995, more and more papers on the topic of landslide hazard and risk were being published. For example, in the proceedings of the *5th International Symposium on Landslides,* held in Switzerland, among the many papers published, two are particularly relevant. The first by Dr. Herbert Einstein (Massachusetts Institute of Technology) is a special lecture entitled *Landslide risk assessment* (Einstein 1988), and the second by Dr. E.W. Brand (Geotechnical Engineering Office, Hong Kong) is entitled *Landslide risk assessment in Hong Kong* (Brand 1988).

Another related facet of the story is that the United Nations designated the 1990s the *International Decade for Natural Disaster Reduction*. Its basic objective was to decrease the loss of life, property destruction and social and economic disruption caused by natural disasters, including landslides. In his introductory remarks, then UN Secretary General, Javier Perez de Cuellar, stated, *"A fundamental precondition for improvements in risk-assessment and disaster management capabilities is the availability of reliable historical data on disasters on a country-by-country basis"* (Cruden and Fell 1997b).

4.8 1985-1995 Summary

By the end of the period 1985-1995, landslide hazard and risk analysis was accepted and was starting to be encountered in geotechnical practice although mainly in western Canada. Qualitative analysis was still dominant, but quantitative analysis was starting to make inroads. Except in a few isolated cases, what was lacking was tolerable or acceptable landslide risk criteria, to allow risk evaluation to complete the risk assessment.

5. 1995-2005: INTEGRATING NEW KNOWLEDGE

The period 1995-2005 saw a flurry of studies and publications associated with landslide hazard and risk in

Canada, and abroad. Not everything can be covered in this paper and only some of the more relevant publications are introduced.

5.1 (US) Transportation Research Board, Special Report 247

In 1996, the (US) Transportation Research Board published its Special Report 247 *Landslides: Investigation and Mitigation* (Turner and Schuster 1996). As mentioned in Section 3.5, this publication was the successor to Special Report 176 (Schuster and Zrizek 1978) and Special Report 29 (Eckel 1958). Special Report 247, for the first time in this series of publications, includes a chapter on *Landslide hazard and risk assessment* (Wu et al. 1996). This relative short, 13-page chapter, briefly introduces the topic and the concepts. Although the word 'assessment' is used in the title, the chapter does not develop the concept of tolerable or acceptable landslide risk criteria.

5.2 BC Ministry of Forests, Part 1

In BC in 1995 and 1996, the BC MOF codified how geotechnical professionals should carry out qualitative landslide analyses. This was published as the *Mapping and Assessing Terrain Stability Guidebook*, in support of the 1995 *Forest Practices Code of British Columbia Act* (BC MOF 1995 updated in 1999), and *Terrain Stability Mapping in British Columbia: a review and suggested methods for landslide hazard and risk mapping* (BC RIC 1996b).

5.3 Saguenay Region, Québec

Elsewhere in Canada, a major flood occurred in July 1996 in the Saguenay Region of Québec and resulted in the loss of land, buildings, infrastructure and life. As reported in Hungr and Locat (2015) this flood *"prompted a new law [in Québec] to address various aspects of landslide hazard assessment and public safety. In support of this legislation, the responsibility for landslide hazard mapping in Québec was given to the 'Section des mouvements de terrain', within the Ministère des Transports du Québec, in cooperation with the Ministère de la Sécurité publique du Québec."* Guidelines and details about the hazard mapping process and methodology are described in Robitaille et al. (2002), Bilodeau et al. (2005) and Demers et al. (2008).

5.4 International Workshop on Landslide Risk Assessment, Honolulu, HI

In 1996, at the *7th International Symposium on Landslides,* in Norway, the International Union of Geological Sciences' Working Group on Landslides (formerly the International Geotechnical Societies'[6] Working Party on the World Landslide Inventory) formed a Committee on Risk Assessment with Dr. Fell as Chair (Cruden and Fell 1997b). Its objectives included:

- to review terminology and to propose internationally acceptable definitions of terms used in assessing the risk of landslides;
- to review national standards of acceptable and tolerable risk and to suggest methods of applying these to landslide risk assessment; and
- to review methods of predicting vulnerability of property and life to landslides.

As part of that committee's mandate, in 1997, Dr. Cruden and Dr. Fell organized the *International Workshop on Landslide Risk Assessment,* in Hawaii (Cruden and Fell 1997a). Workshop attendance was by invitation and each invitee had to present a paper. Outcomes of the discussions held during the workshop are summarized in a state-of-the-art paper in the proceedings (IUGS Working Group on Landslides, Committee on Risk Assessment 1997).

Of the 38 attendees at this workshop, 14 (more than 1/3) were from Canada, indicating that Canada was seen as a leader in this field. To give an idea of this leadership, the following papers were presented by Canadians and their affiliation at that time:

- a theme paper entitled *Toward landslide risk assessment in practice* (Morgenstern [University of Alberta], 1997);
- a theme paper entitled *Landslide risk management* (Fell [University of New South Wales, Australia] and Hartford [BC Hydro 1997);
- *Estimating the risks from landslides using historical data* (Cruden [University of Alberta] 1997);
- *Fatal landslides and landslide risk in Canada* (Evans [Geological Survey of Canada] 1997);
- *BC Hydro's approach to evaluating reservoir slope stability from a risk perspective* (Imrie and Moore [BC Hydro] 1997);
- *Some methods of landslide hazard intensity mapping* (Hungr [University of British Columbia] 1997);
- *Landslide stages and risk assessment issues in sensitive clays and other soft sediments* (Locat and Leroueil [Univérsité Laval] 1997);
- *Management of rock slopes on the Canadian Pacific Railway* (Mackay [CP Rail] 1997);
- *A regulatory perspective on slope hazards and associated risks to life* (Morgan [Consultant] 1997);
- *Integrating risk and crisis management: meeting the needs of a sophisticated society* (Oboni and Oldendorff [Consultants] 1997);
- *Landslide hazard and risk assessments for small projects, preliminary studies and emergency response* (VanDine [Consultant] 1997).

Fell and Hartford (1997) present a comprehensive review of tolerable and acceptable landslide risk criteria, including F-N diagrams, used in other fields of engineering, a discussion of several publications from the late 1980s and early 1990s by the [UK] Health and Safety Executive (summarized later in HSE 2001) and the F-N diagram adopted by the Hong Kong Government Planning Department for potentially hazardous industries (Hong Kong 1994). Their review also introduces the concept of

[6] The International Geotechnical Societies are the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE), the International Society of Rock Mechanics (ISRM) and the International Association of Engineering Geology (IAEG).

ALARP (as low as reasonably practicable) into the landslide risk vocabulary.

Fell and Hartford (1997) make the point that geotechnical professionals should not establish tolerable and acceptable landslide risk criteria, but only provide guidance to those who do so. Morgan (1997) concludes with *"The prime advantages to [quantitative] risk assessment are that it encourages a structured approach to understanding failure mechanisms and their consequences, and that it facilitates objective communication between engineers and non-engineers who are frequently decision makers."* Both these important points have been reiterated many times since.

5.5 Canadian Standards Association

In Canada, in 1997, the Canadian Standards Association (CSA) first published its *Risk Management: Guideline for Decision Makers"* (CSA 1997). This standard evolved from the 1991 CSA publication *Risk analysis requirements and guidelines* (CSA 1991). Although neither publication were written specifically for landslides, many subsequent landslide hazard and risk assessment publications in Canada have made use of the concepts and terminology presented in these standards; for example, Wise at al. (2004).

5.6 Hong Kong GEO Report No. 75

In 1998, the Hong Kong Geotechnical Engineering Office (HK GEO) published GEO Report No. 75 entitled *Landslides and Boulder Falls from Natural Terrain: Interim Risk Guidelines* (ERM-Hong Kong Ltd 1998). After a very thorough world-wide review of risk criteria for major hazard installations handling dangerous goods, railway operations and dams, recognizing that *"there are no established criteria backed by a government for landsliding"*, and considering little distinction between *"man-made and natural hazards"* where permitting by government is involved, the report recommends, with a few caveats, the following landslide risk criteria:

For individual risk:

- *"the maximum allowable individual risk level to a member of the public in a new development from any natural terrain landslides and boulder falls should not exceed 10^{-5} per year", and*
- *for existing developments it is proposed that the maximum individual risk to which any member of the public should be exposed from natural terrain landslides and boulder falls is taken to be 10^{-4} per year."*

For societal risk, the report recommends two options, shown as F-N diagrams (Options X and Y) (see Figure 4). The report added, *"It is strongly recommended, however, that the societal risk criteria should not be mandatory, and should be used as guidelines only."* (ERM-Hong Kong Ltd 1998). (Note that the recommended Hong Kong societal risk criteria are more conservative than the aforementioned criteria presented by Morgan (1992), shown on Figure 3.)

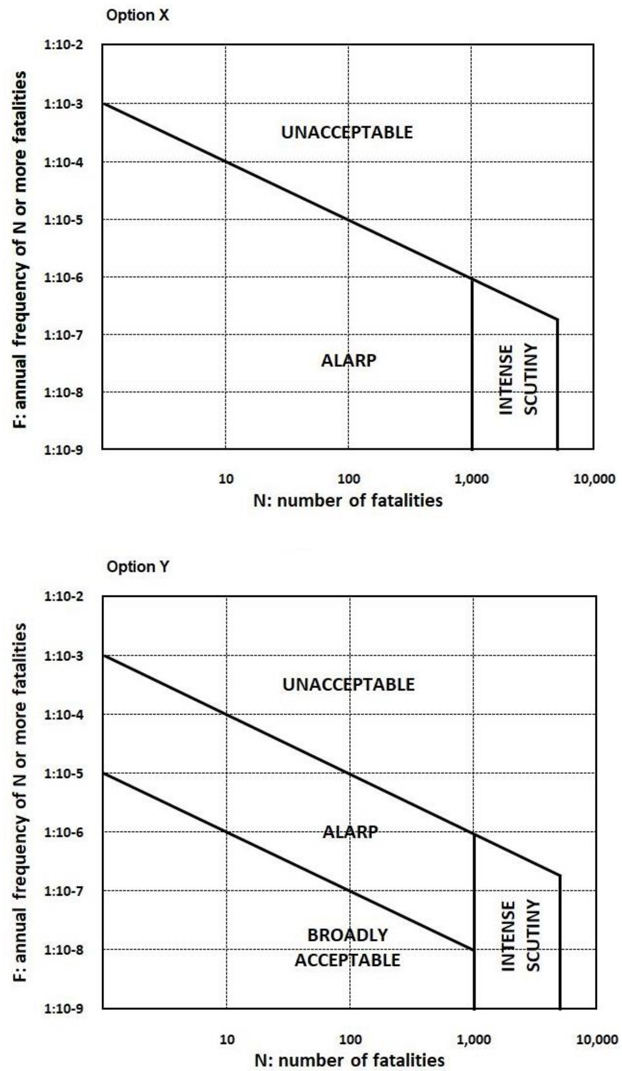

Figure 4: Recommended societal landslide risk criteria Options X and Y adapted from HK GEO Report No. 75 (ERM-Hong Kong 1998).

Subsequent to GEO Report No. 75 being published, Option X appears to have become the preferred F-N diagram for societal risk from natural terrain landslides and boulder falls in Hong Kong; see for example Malone (2005) and Wong (2005). Option Y, however, appears to be the preferred *"conventional approach"* elsewhere in the world; see for example Leroi et al. (2005). As discussed later, the recommendations from GEO Report No. 75 will become an important element in the story of landslide risk assessments in Canada.

5.7 GeoHazards 2, Montreal, QC; GeoHazards 3, Edmonton, AB

In 2000, the CGS, the Geological Survey of Canada and Emergency Preparedness Canada held the *Canadian Workshop on Geotechnique and Natural Hazards:*

Achievements and Prospects, in Montreal, QC (Couture and Evans 2000). This workshop, nicknamed GeoHazards 2, was organized to mark the closing of the International Decade of Natural Disaster Reduction. Of the five presentations related to landslides, only one presentation (Hungr 2000) was related to landslide hazard and risk analysis and assessment.

In 2003, the CGS and the Geotechnical Society of Edmonton held the *3rd Canadian Conference on Geotechnique and Natural Hazards,* in Edmonton, AB (Lewycky and Froese 2003). Nicknamed GeoHazards 2003 or GeoHazards 3, the proceedings only include a few papers and case studies related to landslide hazard and risk. Of greater interest, perhaps, GeoHazards 3 was preceded by a one-day workshop on landslide hazard and risk assessment, organised by the Department of Civil & Environmental Engineering, University of Alberta. This workshop, and the many reprints provided, thoroughly reviewed various aspects and some case studies of the topic on a world-wide basis. This workshop brought many Canadian practitioners and academics up-to-date on the topic.

5.8 Railway Ground Hazard Research Program

Also in 2003, the Railway Ground Hazard Research Program (RGHRP) was established. It is a collaborative effort among Canadian industry, universities and the federal government intended to "*develop and evaluate scientific and technical solutions to help railways manage the risks associated with ground hazards*" (RGHRP, no date). The partners include the University of Alberta, Queen's University, Transport Canada, the Geological Survey of Canada and both the Canadian National and the Canadian Pacific railways. This program has resulted in a significant amount of practical research involving more than 50 graduate students, and has led to many advances in various aspects of landslide hazard and risk analysis. Although the emphasis is rail transportation, the results can be, and have been, applied to many other areas. Over the past 15 years, this relatively unique collaborative initiative has helped make Canada a world leader in railway safety (Hendry et al., 2012)

5.9 BC Ministry of Forests, Part 2

By 2004, the BC MOF was beginning to formalize landslide hazard and risk analyses. To assist in this transition, it published a handbook on *Landslide Risk Case Studies in Forest Development Planning and Operations* to *"help provide a rational basis for informed and defensible decisions pertaining to landslide risk management associated with forest practices in British Columbia"* (Wise et al. 2004). This handbook presents a framework for landslide risk management, adapts the decision-making process outlined in CSA (1997) to landslides, describes hazard and risk terminology and methods specifically in terms of landslides, and presents eight qualitative and quantitative landslide analysis case studies prepared by geotechnical professionals. It presents examples of qualitative risk matrices and a quantitative event tree analysis.

5.10 International Landslide Risk Management Conference, Vancouver, BC

In 2005, as a follow up to the 1997 *International Workshop on Landslide Risk Assessment* (Cruden and Fell 1997) (see Section 5.4), the Joint Technical Committee on Landslides and Engineered Slopes (JTC-1)[7] and the Vancouver Geotechnical Society held the four-day *International Landslide Risk Management Conference* in Vancouver (Hungr et al. 2005). The conference and proceedings includes eight state-of-the-art papers, four invited papers, eight papers on national landslide risk strategies, and 35 case studies and other submitted papers. Seventeen of the above papers are authored or co-authored, by Canadians, representing contributions from British Columbia, Alberta, Ontario, Quebec and Newfoundland and Labrador. An invited paper from Canada entitled *Landslide risk assessment in Canada: a review of recent developments* (Evans et al. 2005), and the national risk strategy paper from Canada entitled *The role of magnitude-frequency relations in regional landslide risk analysis* (Guthrie and Evans 2005) deal primarily with landslide inventory and hazard analyses.

From the proceeding of this conference, this author considers two state-of-the art papers to be particularly relevant: *A framework for landslide risk assessment and management* (Fell et al. 2005) and *Risk assessment and management* (Leroi et al. 2005).

With regard to tolerable and acceptable landslide risk criteria, Leroi et al. (2005) suggest some common general principles apply. Paraphrased these are:

- landslide risks to an individual should not be significant when compared to other risks to which an individual is exposed in everyday life;
- landslide risk should be reduced wherever reasonably practicable (the ALARP principle);
- if the potential number of lives lost from a landslide is high, the corresponding likelihood that the landslide will occur should be low; this accounts for society's intolerance to many simultaneous casualties, and is embodied in societal risk criteria; and
- higher risks are likely to be tolerated or accepted for existing developments than for proposed developments.

5.11 1995-2005 Summary

By the end of the period 1995-2005, landslide hazard and risk analysis, both qualitative and quantitative, were being integrated into Canadian geotechnical practice. Except in a few isolated cases, tolerable or acceptable landslide risk criteria were still lacking in Canada, thus limiting landslide risk evaluation and, therefore, landslide risk assessment.

[7] JTC-1 is a joint committee of the ISSMGE, ISRM and IAEG.

6 2005-PRESENT: APPLYING NEW KNOWLEDGE

6.1 Guidelines for Legislated Landslide Assessments for Proposed Residential Developments in BC

As introduced in Section 3.1, the 1979 *BC Land Titles Act* states that if land to be subdivided is subject to, or could reasonably be expected to be subject to, a number of listed natural hazards (including landslides), the approving officer may require a report by a geotechnical professional to determine if *"the land may be used safely for the use intended"*. In 1985, amendments to the BC *Municipal Act* required something similar. In 1996, the BC *Municipal Act* was changed to the BC *Local Government Act* and in 2003 a portion of that act was carved off as the BC *Community Charter*. All of these pieces of legislation, and some associated regulations, require geotechnical professionals to carry out landslide risk assessments but, as of 2006, guidelines as to how to carry out such assessments and, for most of BC, defined tolerable or acceptable risk criteria, did not exist[8].

The latter situation put BC geotechnical professionals in a difficult situation. They were being asked to state whether or not a parcel of land was 'safe' from a landslide (among other natural hazards), but no one could or would tell them what was considered to be safe.

In 2006, to help fill the aforementioned gaps, Engineers and Geoscientists BC (EGBC)[9] published *Guidelines for Legislated Landslide Assessments for Proposed Residential Developments in BC* (EGBC 2006). From the introduction, *"This document (1) provides guidelines of professional practice for a Professional Engineer and Professional Geoscientist who carries out a landslide analysis for a proposed residential development, and (2) provides guidance to the professional as to how to relate the results of the analysis to a level of landslide safety [tolerable or acceptable risk criteria] for residential development when required by provincial legislation"* whether or not the approving jurisdiction has adopted tolerable or acceptable risk criteria.

EGBC (2006), and as stated in 2008 and 2010 updates, emphasises that it is not the role of a professional engineer or geoscientist to define tolerable or acceptable risk criteria; those criteria must be established and adopted by the appropriate jurisdiction after considering a range of societal values.

Appendix C of the EGBC document includes a review of tolerable and acceptable landslide hazard and risk criteria in BC, and nationally. The BC criteria, up to 2006, have already been introduced in this paper. Appendix C notes that there were (and there still are) no national tolerable and acceptable landslide hazard and risk criteria. From Appendix C:

- The National Building Code of Canada 2005 (NBCC, 2005) only provides the statement, "*Where a foundation is to rest on, in or near sloping ground, this particular condition shall be provided for in the design."*
- The Canadian Foundation Engineering Manual (CGS, 2006), although it emphasizes foundation engineering, not landslides, contains several references to landslides:
  - *"the possibility of landslides should always be considered, and it is best to avoid building in a landslide area or potential landslide area; and*
  - *when a potential landslide area is identified, the area should be investigated thoroughly and designs and construction procedures should be adopted to improve the stability".*

Appendix D of EGBC (2006) provides a *"Landslide assessment assurance statement"*, patterned after BC Building Code Schedules. The statement, to be completed by the geotechnical professional, provides assurance to the client and the approving jurisdiction that the landslide risk analysis was carried out to a certain standard, and that if a landslide risk assessment was carried out, an appropriate *"level of landslide safety"* (tolerable or acceptable landslide risk criteria) was used for risk evaluation.

EGBC (2006) was well received by geotechnical professionals and approving jurisdictions in BC. It was updated in 2008 and 2010 (EGBC 2008 and 2010), in part, to include reference to the NBCC (2005) and the 2006 BC Building Code (BCBC 2006) and their ground motions for seismic designs. EGBC (2008 and 2010) include specific considerations for seismic slope stability.

6.2 District of North Vancouver, BC

In January 2005, extreme rainfall along the BC coast resulted in a flow slide in the District of North Vancouver (DNV) that destroyed a house and resulted in one fatality and one severe injury. Following this event, the DNV retained BGC Engineering Inc. and over the next four years, they worked closely together to successfully carry out the first comprehensive quantitative landslide risk assessment (the combination of risk analysis and risk evaluation) in Canada (Porter et al. 2007, 2009 and 2011).

In 2009, the DNV became the first municipality in Canada to formally adopt and apply a landslide risk tolerance criteria for individual risk (DNV 2009 and Porter et al. 2017). This involved a significant amount of public consultation and input (Tappenden 2014). The DNV, however, stopped short of adopting societal risk criteria.

In the end, the DNV adopted Hong Kong's landslide risk criteria for individual risk associated with both existing and proposed residential developments (see Section 5.6). The criteria were also established to be compatible with recommended approaches to landslide risk assessments outlined in EGBC (2008 and 2010) including use of the landslide assessment assurance statement and the guidelines for seismic slope stability. The DNV criteria are summarized in Table 4.

The above landslide risk criteria also benefitted from the general principles outlined by Leroi et al. (2005), as presented in Section 5.10.

In 2011, the DNV received the United Nations Sasakawa Award for Disaster Risk Reduction. The following year, the DNV was recognized as an example of

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[8] One exception was the Regional District of Fraser Valley, discussed in Section 4.2

[9] Up until 2017, EGBC was known as the Association of Professional Engineers and Geoscientists of British Columbia (APEGBC).

Table 4. DNV Landslide Risk Criteria adapted from DNV (2009).

Application Type	Risk <1:10,000	Risk < 1:100,000	FS >1.3 (static); 1:475 (seismic)	FS >1.5 (static); 1:2,475 (seismic)
Less than 25% increase in building footprint	X		X	
Repair or replace retaining structure				X
New residence, new retaining structure, or >25% increase in building footprint		X		X

Notes:
1. Risk = annual probability of fatality for individual most at risk
2. FS = limit equilibrium factor of safety for global failure
3. Seismic slope stability criteria based on specified ground motion chance of exceedance and either FS >1.0 or ground deformation <0.15 m in non-liquefiable soils, as per EGBC (2010)
4. In addition to meeting these criteria, landslide risks must be reduced to ALARP so that the cost of further risk reduction would be grossly disproportionate to any risk reduction benefits gained.

innovation and community engagement in the United Nations handbook entitled *How to make cities more resilient* (as reported in Morgenstern 2017). Following its commitment to improve and update its associated policies, the DNV completed a quantitative safety and economic risk assessment for 35 steep mountain creeks in the district (Holm et al. 2017 and CGS 2017).

6.3 GeoHazards 4, Québec, QC

In 2008, the CGS and its Eastern Québec Section held the *4th Canadian Conference on Geohazards* (GéoRisques/GeoHazards 4) in Québec, QC (Locat et al. 2008). During the conference, among other case studies, there were several presentations relating to landslide hazard mapping in Québec following the 1996 Saguenay Region flood: for example the papers by Demers et al. (2008) entitled *La gestion des risques de glissement de terrain dans les sols argileux au Québec (Management of landslide risks in clay soils in Quebéc)*, and by Lefebvre et al. (2008) entitled *Slope stability evaluation: more observation and less calculation*.

6.4 BC Ministry of Transportation and Infrastructure

In 2009, the BC MOTI attempted to clarify its 1993 guidance with respect to acceptable risk criteria for the subdivision approval process (BC MOTI 1993) in an internal document entitled *Subdivision Preliminary Layout Review-Natural Hazard Risk* (BC MOTI 2009 updated in 2013 and 2015). The internal document is accompanied by its website *Guide to Rural Subdivision Approvals–Section 2.3.1.07 Geotechnical Study* (BC MOTI no date). Paraphrased from the internal document, guidance is:

- *"for a building site, unless otherwise specified, ~500-year return period [10% probability in a 50-year period] of a damaging event;*
- *for a large-scale development, an annual hazard probability of a life-threatening or catastrophic landslide a 10,000-year return period [0.5% probability in a 50 year period] event; and*
- *large-scale developments must also consider total risk and refer to international standards."*

The website outlines the method for an assessment:

- *"determine if there is a hazard;*
- *determine extent of any hazard; and*
- *identify building sites free from hazard, or where risk could be rendered acceptable."*

As discussed in Section 3.1, the BC MOTI's criteria of the *"~500-year return period event"* was based on the 1985 National Building Code of Canada (NBCC 1985), which referred to earthquake probability for ground motions for seismic building design to minimize loss of life, and the *"10,000-year return period event"* was based on the 1973 Justice Berger ruling (VanDine and Lister 2011).

This guidance has not been published to date, and until the terms *"damaging", "life-threatening", "free from hazard"*, and *"where risk could be rendered acceptable"* are more clearly defined, the BC MOTI should be contacted for further clarification.

6.5 National Technical Guidelines and Best Practices on Landslides

Beginning in 2010 and continuing to 2016, the Geological Survey of Canada (GSC) embarked on an initiative to document *National Technical Guidelines and Best Practices on Landslides* as part of the Natural Resources Canada, Geoscience for Public Safety Program's *"national initiative for loss reduction"*. The intent was *"to provide Canadian engineers, geoscientists and other landslide practitioners with a state-of-the-art document related to the science and applied science of landslides* *and associated loss reduction*" (Couture et al. 2011). The initiative was modelled somewhat after similar initiatives in Australia (Australian Geomechanics Society 2007), and Europe's Safeland project (see for example, Corominas and Mavrouli 2011).

The initiative resulted in 11 GSC Open File reports (Bobrowsky 2016) with contributions from more than 60 Canadian landslide specialists. The Open File reports of particular interest to landslide hazard and risk assessment, include *Risk management* (VanDine 2012) and *Risk evaluation and communication* (Porter and Morgenstern 2013; see also Porter et al. 2017). These two Open File reports were updated in 2015, but have not yet been published. Several other Open File reports have been referenced in this paper (Jackson et al. 2012, Hungr and Locat 2015 and Lato et al. 2016).

In 2009, the International Organization for Standardization (ISO) released a guidance document related to risk management (ISO 2009). The guidance *"is not specific to any country, industry or sector and is intended for use by any public, private or community enterprise, association, group or individual".* In 2010, the Canadian Standards Association adopted ISO (2009) as the Canadian national standard (CSA 2010a), and published a draft companion document to help implement the new standard (CSA 2010b). Neither of these documents are specific to landslides. As part of the GSC's *National Technical Guidelines and Best Practices on Landslides*, VanDine (2012) adapts the 2009 ISO document to landslides.

Porter and Morgenstern's (2013) contribution to the GSC's initiative states that *"there are considerable benefits to establishing provincial and/or national landslide safety criteria. Such benefits include:*

- *more consistent landslide safety criteria between local governments and provinces;*
- *improved communication between developers, landslide professionals, approving authorities, insurance providers, real estate agencies, and the public; and,*
- *in some cases reduced levels of landslide risk in jurisdictions where criteria have not been established.*

To be applicable across geographically diverse regions and a wide range of development scenarios, such guidelines likely require reference to a range of landslide risk evaluation and risk assessment methods and recommendations to landslide professionals on which methods are appropriate for given conditions and circumstances."

Porter and Morgenstern (2013) then suggest the following criteria as appropriate for proposed new residential development:

- *"<1:10,000 per annum probability for a landslide occurring and reaching the area of proposed development;*
- *<1:100,000 per annum risk of loss of life to individuals most at risk;*
- *group or societal risk of loss of life evaluated on an F-N curve, with the ALARP or broadly acceptable regions as the landslide safety criteria;*
- *tolerable slope deformation under seismic loading = 0.15 m (where it can be demonstrated that soils are not prone to earthquake-triggered liquefaction); and,*
- *where appropriate, an allowance for 100 years of predicted toe erosion along river, lake, ocean, or reservoir shorelines.*

It is suggested that less stringent criteria, that is, risks up to one order of magnitude higher, may be appropriate for ongoing occupation of, or the approval of minor modifications to, existing residential development. Greater risks may also be tolerable for employees of organizations with infrastructure exposed to known landslides, provided systematic procedures are followed to understand, prioritize and manage the risks."

The intent was that the GSC would update and translate the 11 Open File reports, and compile and release them in a single document as a GSC Bulletin (Bobrowsky 2016). It currently appears that this is not going to occur (Bobrowsky, personal communication).

6.6 GeoHazards 5, Kelowna, BC; GeoHazards 6, Kingston, BC

In 2011 and 2014, the CGS and its Interior BC and Kingston sections, respectively, held the *5th Canadian Conference on Geotechnique and Natural Hazards* (GeoHazards 2011 or GeoHazards 5) in Kelowna, BC, and the *6th Canadian GeoHazards Conference* (GeoHazards 6) in Kingston, ON. At each conference several case studies were presented that were related to landslide hazard and risk analysis and assessments (Tannant and Guthrie 2011 and Gauthier et al. 2014). GeoHazards 6 was followed by a one-day workshop on *Geohazard Risk Communication, Perception and Tolerance*.

6.7 Professional practice guidelines–legislated flood assessments in a changing climate in BC

In 2012, EGBC published parallel guidelines to its *Guidelines for Legislated Landslide Assessments for Proposed Residential Developments in BC* (EGBC 2006 revised in 2008 and 2010) related to flooding. The 2012 document is entitled *Professional Practice Guidelines–Legislated Flood Assessments in a Changing Climate in BC* (EGBC 2012). These latter guidelines, specifically Appendices E and F, discuss flood hazard mapping, and flood risk analysis, evaluation and tolerance criteria. Although flooding is emphasized, debris floods and debris flows are included.

With regards to debris flood and debris flow hazard mapping, Appendix E suggests typical hazard mapping methods, return periods and associated proposed development that should be considered for different 'classes' of debris floods and debris flows (Table E-2). The return periods for debris floods and debris flows only go to 2,500 years. This is in line with the NBCC (2005) design earthquake of 1:2,500. In addition, it was felt that the uncertainty associated with estimating a 10,000-year return period event is so large and challenging, that a 2,500-year return period event is sufficiently conservative (Matthias Jakob, personal communication).

Appendix J of EGBC (2012) provides a *Flood hazard and risk assurance statement*, similar to Appendix D of the EGBC landslide guidelines (EGBC 2006 revised in 2008 and 2010).

6.8 11th International and 2nd North American Symposium on Landslides and Engineered Slopes, Banff, AB

Also in 2012, the *11th International and 2nd North American Symposium on Landslides and Engineered Slopes* was held in Banff, AB, under the auspices of the Joint Commission on Landslides and Engineered Slopes (JTC-1)[10] (Eberhardt et al. 2012). This major international symposium included 13 keynote and invited papers, the prestigious 1st Heim Lecture, and several hundred presentations from all over the world, organized into six sessions. Only a few keynote or invited papers, however, are related to the topic of landslide hazard and risk, and then only indirectly. The session in which this topic is included, contains only a few papers directly related to landslide hazard and risk analysis and assessment in Canada. One of the more relevant is a paper by Porter and Morgenstern (2012) entitled *Landslide risk evaluation in Canada*, submitted at the request of the symposium organizers. It is very similar to, what was soon to be published as, Porter and Morgenstern (2013), discussed in Section 6.5.

6.8 Canmore, Alberta

In 2013, extreme rainfall events in the Town of Canmore and area, Alberta, resulted in flooding, debris floods and debris flows that damaged and destroyed a number of residences and associated infrastructure, and resulted in one of Canada's most costly natural disasters. Following these events, Canmore retained BGC Engineering Inc. to carry out comprehensive debris flood or debris flow hazard (Jakob et al. 2017) and risk assessments (Holm et al. 2018) for five creeks within its boundaries. The assessments focused primarily on direct building damage, injury, and loss of life. Initially on an interim basis, Canmore adopted the same individual risk tolerance criteria as the District of North Vancouver, BC, described in Section 6.2, and societal risk tolerance criteria based on Hong Kong's F-N Diagram Option Y (Canmore, Town of 2015), shown in Figure 4 in this paper.

In 2014, prior to selecting final mitigative options, Canmore organized focus groups of both affected and non-affected residents to help in its planning process. Canmore's decisions on risk mitigation were driven by reducing the individual risk and the societal risk to within the ALARP zone on Figure 4 (Option Y). The decisions required consideration of issues of *"feasibility, fairness, and affordability"* (Morgenstern 2017).

In 2016, Canmore approved a *"Steep creek hazard and risk policy"* (Canmore 2016). From that policy:

"Two metrics are used to measure safety risk:

a. Individual risk is the risk of an individual being killed in an event. Individual Risk can be assessed for persons in any given year. Individual risk takes into account the magnitude and frequency of the hazard, the location of the person exposed to the risk and the structure type for persons within buildings, and the probability of a person being present during an event. The resultant measure is referred to as the Annual Probability of Death of an Individual or PDI.

b. Group risk is the potential for multiple deaths in a single event. A greater number of persons exposed to the same hazard results in increased risk. As society has a very low tolerance for group risk, new development needs to be maintained within acceptable thresholds. Often, with existing development, it is prohibitive socially, economically, and environmentally to reduce risk into 'Acceptable' ranges. In those cases the Town endeavors to reduce group risk to 'As Low As Reasonably Practicable' (ALARP). Where group risk is determined to be unacceptable, the Town may limit new development that results in an increase to group risk until action is taken by the Town to reduce group risk to 'Acceptable' or 'ALARP'."

Economic cost is also included in this policy. By approving this policy, Canmore became the first Canadian jurisdiction to adopt legally binding societal risk criteria.

Canmore's use of a quantitative risk assessment approach was seen as being useful to gain stakeholder support, and in so doing, Canmore benefited from partial funding from the Province of Alberta.

6.9 Cheekye Fan, BC, Part 2

Between 2013 and 2015, two review panels were appointed by the Province of BC, the Squamish Nation and its Partnership, and the District of Squamish to review proposed residential development on the lower Cheekye Fan, north of Squamish, BC (refer to Section 4.5). The panels consisted of Dr. John Claque (Simon Fraser University), Dr. Hungr (University of British Columbia), Dr. Morgenstern (University of Alberta, second panel only) and this author. Since the joint Thurber Engineering Ltd.-Golder Associates Ltd. study in 1993 (see Section 4.5), further landslide risk analyses had been carried out by Kerr Wood Leidal Associates Ltd., BGC Engineering Inc. and several independent consultants and researchers. These resulted in a revised proposal to develop the fan for an approximate 750-lot residential subdivision.

The two review panels were asked to review all the information gathered to date, including letters by a 2007-2008 review board[11] and a 2013 review by Golder Associates Ltd. The first review panel provided its opinions on the possibility and character of future landslides, including debris flows and debris floods, and possible effects of climate change; the second review panel provided advice on aspects of individual and societal landslide risk tolerance criteria for the existing and the proposed development on the fan.

The specific results of these two review panels are not public. However, with permission, the second review panel's thorough review of risk tolerance criteria

[10] JTC-1 is a joint committee of the ISSMGE, ISRM and IAEG.

[11] The 2007-2008 Review Board consisted of Dr. Morgenstern, Dr. Hungr and Dr. Andrew Robertson.

throughout the world was published in the proceedings of the 2016 *12th International Landslide Symposium* in a paper entitled *A review of landslide risk acceptability practices in various countries* (Hungr et al. 2016). Much of that paper, as it relates to the evolution of landslide hazard and risk assessments in Canada, has already been presented in this paper.

6.10 Dr. Hungr, 2016; Dr. Morgenstern, 2017

The most recent contributions to landslide hazard and risk assessment in Canada are two international presentations given by prominent Canadians. The first was the prestigious 2nd Heim Lecture presented at the *12th International Landslide Symposium*, held in 2016 in Italy. Dr. Hungr's presentation was entitled *A review of landslide hazard and risk assessment methodology* (Hungr 2016).

From Dr. Hungr's conclusion, *"considerable advances have been made in our field, especially in the areas of monitoring, remote sensing and various types of analysis. Nevertheless, our profession continues to rely on a mixture of skills: 1) observation and measurement, 2) experienced judgment and 3) analysis. If a reliable [risk] assessment is to be achieved, each of these three components must be included. Results of all three should be continually cross-checked."*

The second presentation was a 2017 *Distinguished Lecture* presented to the Hong Kong Institution of Engineers by Dr. Morgenstern (Morgenstern 2017). The presentation was entitled *The evaluation of slope stability: a further 25-year perspective*, and expanded upon Dr. Morgenstern's previous 25-year evaluation (Morgenstern, 1992) (see Section 4.6). As part of the 2017 presentation, Dr. Morgenstern made the point that Hong Kong was the leader in establishing landslide risk acceptance criteria and to date only two other jurisdictions in the world have followed Hong Kong's lead and established legally binding regulations in public policy relating to landslide risk: the District of North Vancouver, BC and the Town of Canmore, AB.

In his presentation, Dr. Morgenstern used these two Canadian cases as positive examples, and discussed the importance of having the jurisdiction, stakeholders and decisions-makers all involved in the landslide risk evaluation process.

Dr. Morgenstern concluded his presentation by stating that *"the increased adoption of [quantitative risk assessment] methodologies to strengthen risk-informed decision making, both in private organizations and in public policy, at least for communities of sufficient technological maturity"*, are a positive step forward because such methodologies systematically consider (*honour*, in Dr. Morgenstern's words) all relevant information.

6.11 2005-Present Summary

The period 2005-present is not over. During this period to date, however, landslide hazard and risk assessments in Canada have been applied in at least two jurisdictions with the adoption and application of tolerable and acceptable landslide risk criteria. To date, approximately 30 quantitative landslide risk assessments have been completed in Canada, however, mostly in BC. In addition, there are indications that government policy in some Canadian jurisdictions is also starting to move in this direction.

7 CONCLUDING REMARKS

This paper is written from a somewhat personal perspective because, coincidently, much of the evolution of landslide hazard and risk assessments in Canada has occurred during this author's professional career. It has been a difficult topic to summarize because of the magnitude and complexity of the topic, and because the topic is still evolving.

Some subject areas that this author believes could be studied or further studied include: the practicality of reliably estimating hazards in the 10,000-year to 100,000-year return period range; the applicability of the currently adopted societal risk criteria in areas with lesser population densities; the economic practicality of reducing risks to meet the adopted risk criteria; how to better estimate elements such as vulnerability and runout; better education of decision markers in the area of landslide hazard and risk assessments; and how to include climate change in the analyses.

It is hoped that with what has come before, as presented in this paper, landslide hazard and risk assessments in Canada will continue to evolve. Canada and Canadians have been leaders in this field and this author believes that, somewhat out of necessity because of the challenging terrain found in specific regions of the country, they will continue to be so.

I dedicate my presentation and this paper to the memory of one of these leaders, Dr. Oldrich Hungr (1947-2017), a colleague and a friend for many years.

8 ACKNOWLEDGEMENTS

I am honoured to have been asked to prepare and make this keynote presentation and to prepare this paper. Doing so has given me time to read, review and reflect on the topic. For that I thank the Conference Organizing Committee of GeoHazards 7.

Throughout my career there have been many individuals who have contributed to my knowledge of landslide hazard and risk assessments. I can't list them all, but I thank them all. In particular, in the preparation of this presentation and paper, I would like to thank Mr. Mike Porter, Mr. Graham Morgan, Dr. Matthias Jakob, Dr. Scott McDougall and Dr. Norbert Morgenstern. However, I take full responsibility for any errors or omissions. Dr. Andrée Blais-Stevens kindly translated the abstract.

Because of the length of this paper, I have had to leave out reference to some publications, however, if readers know of any other advancements not included, please let me know.

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