

Cheekye River (Ch'kay Stakw) and Fan Landslide Risk Tolerance Criteria

Report of the Cheekye Expert Review Panel #2

**Dr. John J. Clague P.Geo.
Dr. Oldrich Hungr P.Eng./P.Geo.
Dr. Norbert R. Morgenstern P.Eng.
Mr. Douglas VanDine P.Eng./P.Geo.**

Prepared for:

**Province of British Columbia
Squamish Nation and its Partnership, and
District of Squamish**

June 8, 2015

Copy. Original signed and sealed

Copy. Original signed and sealed

Dr. John J. Clague P.Geo.

Dr. Oldrich Hungr P.Eng./P.Geo.

Copy. Original signed and sealed

Copy. Original signed and sealed

Dr. Norbert R. Morgenstern P.Eng.

Mr. Douglas VanDine P.Eng./P.Geo.

Executive Summary

Introduction and Background

In March 2015, the Province of British Columbia, Squamish Nation and its Partnership, and District of Squamish collectively selected and appointed an independent Cheekye Expert Review Panel (Panel #2). Panel #2 was instructed to use the results of the 2013-2014 Cheekye River and Fan Expert Review Panel (Panel #1) Report (Clague et al. 2014) to review current worldwide landslide risk tolerance criteria and, from its collective experience, provide advice with respect to:

- Task 1: landslide risk tolerance criteria for existing and proposed new development on Cheekye Fan;
- Task 2: current levels of individual and societal risk from landslides on Cheekye Fan;
- Task 3: individual and societal risk reduction that might be achieved through mitigation, given existing and proposed new development; and
- Task 4: whether individual and societal landslide risk tolerance criteria can be applied across the District of Squamish or solely to Cheekye Fan.

Landslide risk tolerance criteria are thresholds, beyond which estimated risk from landslides is considered unacceptable.

This Report summarizes Panel #2's findings, opinions, and recommendations. The focus of Panel #2 was on risk to life.

In order to live in mountainous areas, individuals and society must be prepared to tolerate some risks from landslides. Small landslides occur frequently on steep slopes. Large landslides occur much less frequently, but can have much greater effects. It is not practical to reduce these landslide risks to zero. However, every day, individuals live with risks of dying. The side bar to the right provides examples of an individual's annual risk of dying from some everyday activities and causes. Individual and societal risks are discussed further in Sections 3.3 and 3.4 of this report.

Individual Risk

Examples of an individual's annual risk of dying from select everyday activities or causes:

Voluntary risks:

*smoking 1:200
canoeing 1:500
skiing 1:10,000 for 100 hrs/year
road accidents in BC 1:10,000 (2009 to 2013)*

Involuntary risks:

*electrocution 1:65,000
wildlife-related vehicle collisions in BC 1:1,500,000 (2000-2005)
lightning strike 1:5,000,000*

A number of jurisdictions in the world have established landslide risk tolerance criteria. Although experts can provide valuable input for determining landslide risk tolerance criteria, stakeholders and jurisdictional decision-makers ultimately have to select, by means of an appropriate public process, appropriate risk evaluation parameters (hazard probability, and landslide volume and/or peak discharge) for a particular situation or jurisdiction. This selection has to balance risks from landslides with societal values. Societal values include things such as public safety, affordable residential land, and return on investment.

Once landslide risk tolerance criteria have been established and appropriate risk evaluation parameters have been selected, communities can choose a number of options to meet the criteria. For example, communities can choose not to develop areas that could be affected by landslides, or they can choose to construct some form of engineered mitigation structure, or a combination of options.

The purpose of this report is to provide expert opinions and recommendations to help stakeholders, including citizens, and jurisdictional decision-makers, better understand landslide risk and make informed decisions about landslide risk tolerance criteria, hazard probability, and landslide volume and/or peak discharge for existing and proposed development on Cheekye Fan.

Landslide risk is the combination of the probability that a landslide will occur (hazard probability) AND the expected consequences if it does occur (see side bar to the right for a brief explanation of risk). Section 3 of this report reviews risk and risk assessment.

Section 4 of this report reviews the development of risk tolerance criteria throughout the world, from the industrial and nuclear engineering fields, to dam safety, and finally to landslides. Because hazard probability is more commonly used than risk for the management of landslides in most jurisdictions around the world, landslide hazard probability tolerance criteria are also reviewed.

Risk

In its simplest form, landslide risk can be expressed as:

$R = P_H \times C$, where:

R is the risk,

P_H is the probability of a landslide occurring (hazard probability), and

C is the consequence.

Hazard probability is expressed in terms of a statistical return period. For example a landslide, with an annual hazard probability of 1:1,000 is often referred to as a 1,000-year return period event. It is important to realize that this does not mean that the landslide will ONLY occur once every 1,000 years.

Consequences are expressed in values ranging from 0 (no consequence) to 1 (total loss).

When annual hazard probability and consequence are combined, the resulting annual risk of loss from a landslide is typically expressed as a small number. For example 1:10,000 means that every year there is a one-in-10,000 chance of a loss occurring as a result of the landslide.

Based on its review of landslide risk tolerance criteria throughout the world, Panel #2 has determined that only Hong Kong (in 1998), the District of North Vancouver, BC (in 2009), and the Town of Canmore, Alberta (in 2014) have successfully used quantitative risk assessments for landslides. Quantitative risk assessments require that landslide risk tolerance criteria be established in the respective jurisdictions. The District of North Vancouver and Canmore based their criteria on those of Hong Kong.

Opinions and Recommendations

The following is a summary of Panel #2's opinions and recommendations with respect to Cheekye Fan. Further background and rationale for the opinions and recommendations are presented in Sections 5 and 6 of this report.

Panel #2 Task 1: Advise on landslide risk tolerance criteria for existing and proposed new development on Cheekye Fan.

It is Panel #2's opinion that landslide risk tolerance criteria should be established within the framework of the accepted landslide risk management process (see Section 3.1 of this report). Landslide risk assessment should rely on quantitative risk analysis.

Landslide Hazard Probability

Panel #2, as did Panel #1, recommends that the landslide magnitude-cumulative frequency (total volume-return period) relationship for Cheekye Fan be based on that developed by BGC Engineering Inc. (BGC 2008a) (Figure ES1). On the right side of Figure ES1, the upper, dotted line is the recommended relationship for large landslides.

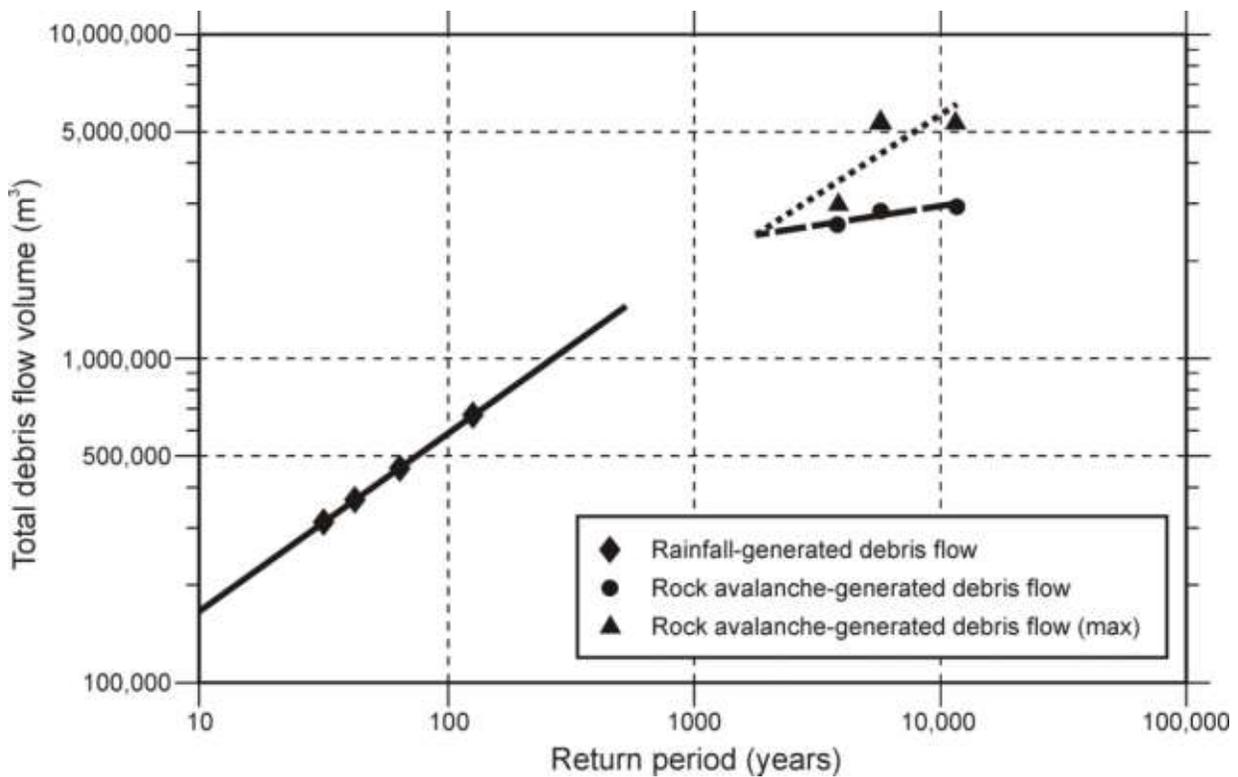


Figure ES1: Magnitude-cumulative frequency relationship for Cheekye Fan (from BGC 2008a). Refer to the Panel #1 report (Clague et al. 2014) for details.

From this relationship, a total debris flow volume can be estimated for each return period.

Landslide Risk Tolerance Criteria

Panel #2 recommends that the Hong Kong landslide risk tolerance criteria should be adopted for Cheekye Fan. The risk-to-life criteria are summarized as:

1. Individual annual risk tolerance should be less than 1:10,000 for existing development and less than 1:100,000 for new development.
2. Societal annual risk tolerance should be based on the Hong Kong Geotechnical Engineering Office F-N diagram (Figure ES2).

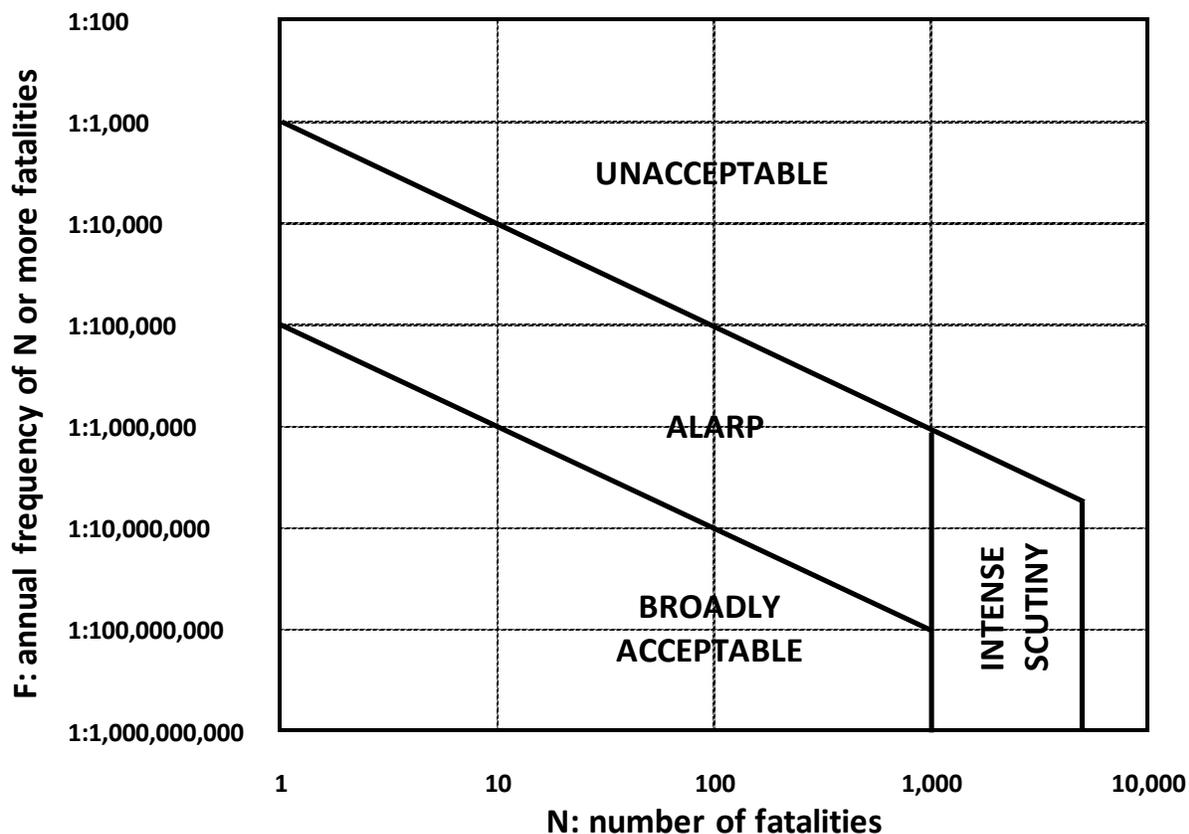


Figure ES2: Recommended F-N diagram for societal landslide risk tolerance criteria for Cheekye Fan (identical to that for Hong Kong).

Estimated societal risks for both existing and new development should fall within the ALARP ('as low as reasonably practicable') zone. 'Reasonably practicable' can be determined qualitatively by qualified professionals, based on costs and: i) land-use decisions and/or land-use restrictions; ii) analyses of the location, layout, and design of engineered structural mitigation; or iii) a combination of both.

Because of the relatively low population density in most of rural BC compared to that of Hong Kong, it is Panel #2's opinion that the 'Intense Scrutiny' zone would seldom be a factor in most landslide risk assessments in rural BC. If it were, however, any associated development would have to be investigated with considerably more than the standard level of effort, as in Hong Kong.

For consistency with Hong Kong practice, the above risk-to-life criteria should be considered as guidelines only and used as one input into the decision-making process.

Risk tolerance criteria cannot be established for elements at risk, other than risk to life. Elements at risk such as property, the environment, and financial interests are typically evaluated by comparing costs of potential losses against costs of preventing those losses (cost-benefit analyses).

Landslide Risk Evaluation Process

The landslide risk evaluation process on Cheekye Fan is a complex undertaking. As mentioned previously, technical input such as this report informs the process, but ultimately the stakeholders and decision-makers must select appropriate risk evaluation parameters (hazard probability, and landslide volume and/or peak discharge). In this regard, the District of North Vancouver and Canmore sought input from stakeholders including citizens.

Stakeholders and jurisdictional decision-makers must consider a variety of competing societal values (see Section 5.2 of this report) when selecting the hazard probability and landslide volume and/or peak discharge (the risk evaluation parameters) that are appropriate to the location and situation. Specifically, selection of the upper limit of the return period will determine the upper limit of the landslide volume and/or peak discharge to be considered in the quantitative risk assessment. In making this choice, some residual risk from not considering larger landslides will be taken (see side bar to the right on residual risk and uncertainty).

Residual Risk and Uncertainty
Residual risk: by analogy, if a 5,000-year return period earthquake occurs and structures are designed for a 2,500-year return period earthquake, there is a residual risk of damage if the larger (less probable) earthquake occurs.
The less probable the hazard (the greater the return period) the more uncertainty there is in the corresponding estimate of landslide volume and/or peak discharge.
Therefore, when an event with a particular return period is selected, if the residual risk is relatively low, the uncertainty in the estimates of landslide volume and/or peak discharge will be relatively high, and vice versa.

Panel #2 recommends that three suites of landslide hazard probability options (Options 1, 2, and 3) be considered (Table ES1 and Figure ES3).

Table ES1: Recommended suites of landslide hazard probability options that should be considered.

Option	Based on a suite of landslide hazard probabilities <u>up to and including</u>	Rationale*
1	10,000-year return period event	Rubble Creek (Berger 1973) Regional District of Fraser Valley (Cave 1992, revised 1993) District of Squamish (2009) BC MOTI (2009 revised 2013)
2	2,500-year return period event	APEGBC (2012) (for debris flows and debris floods) NBCC (2005) (for earthquakes)
3	500-year return period event	BC MOTI (1993, 2009, revised 2013)

*The rationale for these options is explained in Section 5.3 of this report.

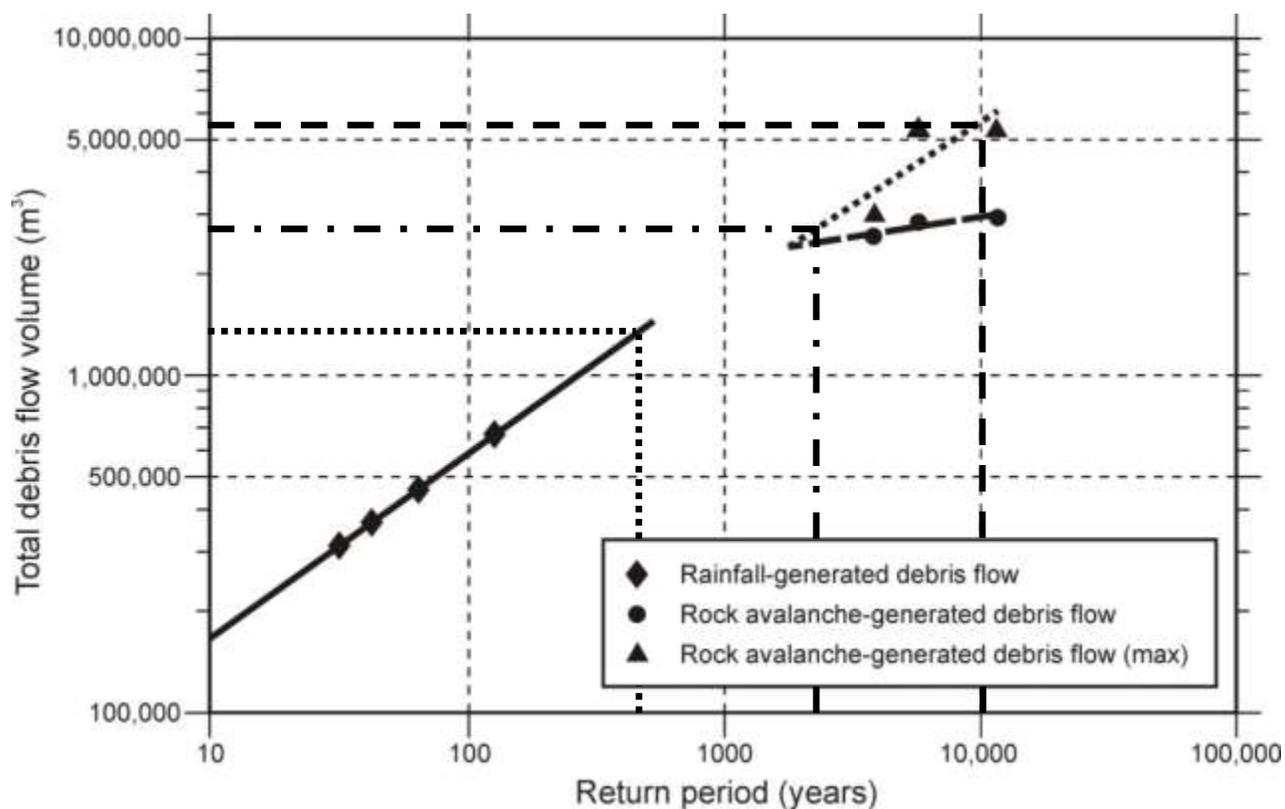


Figure ES3: Magnitude-cumulative frequency relationship for Cheekye Fan (Figure ES1) showing landslide hazard probability options: 10,000-year, 2,500-year, and 500-year return period events and associated total debris flow volumes shown, respectively, as bold dashed, dashed-dotted, and dotted lines.

Stakeholders and jurisdictional decision-makers should also consider, for comparison, the ‘base case’ of no mitigation, or in the case of Cheekye Fan the existing situation of designing for the 200-year return period stream flood. This consideration will help put the landslide hazard probability decision in context.

Options 1, 2, and 3 involve progressively more certainty in estimates of landslide volume and/or peak discharge and less mitigation efforts, but increasing residual risks.

In addition to the above three options, and especially if the landslide risk tolerance criteria presented above were to be applied elsewhere in the District of Squamish, or indeed elsewhere in the province, other suites of landslides hazard probabilities might be considered.

As mentioned previously, Panel #2’s focus was on risk to life. In the landslide risk evaluation process, stakeholders and decision-makers should consider all elements at risk, including those with associated economic losses. Potential economic losses should be quantified, and cost-benefit analysis can be used to guide decision-making.

Panel #2 Task 2: Advise on current levels of individual and societal risk from landslides on Cheekye Fan.

Four draft debris flow model simulation maps were provided to Panel #2 by BGC (Table ES2).

Table ES2: Parameters used for debris flow model simulation maps. All maps at 1:25,000 scale.

Map	Debris flow depths and velocities for return period (years)	Estimated volume (m ³)	Estimated peak discharge (m ³ /s)
1	10,000	5,500,000	33,000
2	10,000	5,500,000	18,000
3	2,500	2,400,000	12,400
4	2,500	2,400,000	7,000

In general, all four maps indicate that approximately two-thirds of Cheekye Fan, and specifically the southern two-thirds of the fan, could be impacted by the simulated debris flows. In all cases the simulated debris flow depths and debris flow velocities would be sufficient to cause considerable damage to buildings and other infrastructure on the impacted portions of the fan and could result in loss of life.

Panel #2 reiterates Panel #1's opinion that the landslide risks to existing development should be mitigated whether or not there is any future development on Cheekye Fan.

Panel #2 Task 3: Advise on individual and societal risk reduction that might be achieved through mitigation, given existing and proposed new development.

Panel #2 was provided conceptual design information for a main barrier and a sedimentation basin that was based on modelling of a 5,500,000 m³ debris flow (the estimated 10,000-year return period event). Based on this information, it is Panel #2's opinion that individual and societal risk reduction to existing and proposed new development could be achieved with some form of engineered structural mitigation, singly or in combination. To be more definitive, the technical feasibility of such structural mitigation, including an examination of detailed designs and operation and maintenance, would have to be examined and considered.

Panel #2 reiterates Panel #1's opinion that, in terms of protecting existing development and possibly allowing some new development on Cheekye Fan, all forms of mitigation, singly or in combination, should be considered and carefully evaluated. To clarify Panel #1's statement, the phrase "all forms of mitigation" could include engineered mitigation structures, such as debris barriers, deflection berms, and terminal berms, as well as non-structural measures, such as land-use zoning, signage, and education.

Panel #2 Task 4: Advise on whether individual and societal landslide risk tolerance criteria can be applied across the District of Squamish or solely to Cheekye Fan.

It is Panel #2's opinion that the landslide risk tolerance criteria described above can be applied across the District of Squamish. However, the magnitude-cumulative frequency relationship shown in Figures ES1 and ES3 is specific to Cheekye Fan; that relationship cannot be used elsewhere. If such a relationship is not available for other locations in the District of Squamish, one would have to be created by qualified professionals.

As mentioned above, there could be justification for considering other suites of landslides hazard probabilities, other than the 10,000-year, 2,500-year, and 500-year return period events described above and shown in Figure ES3, for other locations in the District of Squamish.

Table of Contents

Executive Summary	2
Introduction and Background	2
Opinions and Recommendations	3
Section 1: Introduction	12
1.1 Background	12
1.2 Panel #2 Process	14
1.3 Report	15
1.4 Limitations	16
Section 2: Setting, Development and Previous Studies	17
2.1 Cheekye River Watershed	17
2.2 Lower Cheekye Fan (Cheekye Fan)	19
2.3 Existing and Proposed Development	19
2.4 Previous Studies, Research, and Publications	21
Section 3: Background to Risk and Risk Assessment	23
3.1 Risk Management	23
3.2 Landslide Risk	24
3.3 Living with Landslide Risk	27
3.4 F-N Diagram	27
3.5 Landslide Risk Tolerance Criteria	29
Section 4: Landslide Risk Tolerance Criteria	30
4.1 Risk Tolerance Criteria: Industrial and Nuclear Engineering	30
4.2 Risk Tolerance Criteria: Dams	32
4.3 Risk Tolerance Criteria: Landslides	32
4.4 Landslide Hazard Probability Tolerance	36
Section 5: Advice on Landslides Risk Tolerance Criteria	42
5.1 Landslide Risk Tolerance Criteria	42
5.2 Landslide Risk Evaluation Process	45
5.3 Landslide Risk Evaluation Parameters	46
5.4 Cheekye Fan and the District of Squamish	49
Section 6: Advice on Landslide Risk on Cheekye Fan	50
6.1 Current Levels of Risk	50
6.2 Risk Reduction by Mitigation	51
References	53
Glossary of Some Technical Terms Used in this Report	58

Appendices 60

A: Portion of Terms of Reference (Introduction, Panel Composition, and Scope of Review) for Panel #2, March 25, 2015 60

B: Curricula Vitae of Panel #2 Members 62

Figures

ES1: Magnitude-cumulative frequency relationship for Cheekye Fan 4

ES2: Recommended F-N diagram for societal landslide risk tolerance criteria for Cheekye Fan 5

ES3: Magnitude-cumulative frequency relationship for Cheekye Fan (Figure ES1) showing landslide hazard probability options 7

1: Location map showing the Cheekye and Brohm river watersheds and Cheekye Fan 17

2: Map of the lower Cheekye River and Cheekye Fan 18

3: Portion of District of Squamish OCP, Bylaw 2100, Schedule D1, showing ‘Hazard Zones’ on Cheekye Fan 20

4: Landslide risk management process 23

5: Generic F-N diagram 28

6: F-N diagram showing zones for industrial hazards, as recommended by the United Kingdom Health and Safety Executive 31

7: Societal risk tolerance criteria for landslides in Hong Kong 33

8: Swiss matrix for hazard probability mapping 37

9: Town of Orting, Washington, 50 km distant from Mt. Rainier 38

10: Magnitude-cumulative frequency relationship for Cheekye Fan 43

11: Recommended F-N diagram for societal landslide risk tolerance criteria for Cheekye Fan 44

12: Magnitude-cumulative frequency relationship for Cheekye Fan (Figure 10) showing landslide hazard probability options 47

Tables

ES1: Options of suites of landslide hazard probabilities that should be considered 6

ES2: Parameters used for debris flow model simulation maps 7

1: District of North Vancouver individual landslide risk tolerance criteria 35

2: Options of suites of landslide hazard probabilities that should be considered 48

3: Parameters used for debris flow model simulation maps 50

Section 1: Introduction

This report summarizes the opinions and recommendations of Cheekye Expert Review Panel #2 (Panel #2) with respect to *risk tolerance criteria*¹ for *landslides* at Cheekye River (Ch'kay Stakw)² and Lower Cheekye Fan. The purpose of this report is to provide expert opinions and recommendations to help stakeholders, including citizens, and jurisdictional decision-makers better understand landslide risk and make informed decisions about landslide risk tolerance criteria and the hazard probability and landslide volume and/or peak discharge for existing and proposed development on Lower Cheekye Fan.

In this report:

- 'landslides' include rock slides, *debris flows*, and *debris floods*;
- 'risk tolerance' refers collectively to risk tolerance and/or risk acceptance; and
- 'Lower Cheekye Fan' is referred to as 'Cheekye Fan' because it is the location of most existing and proposed development.

Cheekye River is located approximately 10 km north of Squamish, British Columbia (BC), at the head of Howe Sound, and approximately 70 km north of Vancouver, BC. The Cheekye River watershed and its associated fan complex are one of the most studied watersheds in BC and possibly Canada. Initial geological research dates back to the 1940s. Most of the subsequent geological, geomorphological, and geotechnical studies, research, reports, and publications have been motivated by a series of proposals to develop portions of the fan for residential and other uses, and related questions about landslides and the associated *hazards* and *risks*.

1.1 Background

In late 2013, the Province of BC, Squamish Nation, and District of Squamish collectively selected and appointed the Cheekye River and Fan Expert Review Panel (Panel #1) consisting of Dr. John Clague P.Geol., Dr. Oldrich Hungr P.Eng./P.Geol., and Mr. Douglas VanDine P.Eng./P.Geol. Panel #1 was asked to review all previous relevant documentation and provide its opinion on possible future landslides. Specifically, Panel #1 was instructed to provide its opinions on the:

- volume and frequency of future landslides,
- the character and volume of the 10,000-year return period landslide, and
- possible effects of climate change on future landslides.

Panel #1 did not address landslide risk tolerance criteria. Although Panel #1 was asked its opinion on the character and volume of the 10,000-year return period landslide on Cheekye Fan, it was not asked if, and did not provide an opinion as to whether, a 10,000-year return

¹ Some technical terms are italicized where first used in the text and are defined in the Glossary.

² 'Cheekye' is derived from the Skwxwu7mesh word 'Ch'kay Stakw', which means 'dirty water'.

period landslide is an appropriate risk evaluation parameter on which to base an evaluation of landslide risk tolerance. In addition to providing the above opinions, Panel #1, with permission from its clients, also provided general comments on i) existing risks from debris flows, debris floods, and stream floods to existing development on Cheekye Fan, and ii) considerations for *mitigation*. Panel #1 submitted its report in April 2014 (Clague et al. 2014). The key opinions of Panel #1 were:

Volume and frequency of future landslides

The magnitude-cumulative frequency (MCF) relationship developed by BGC Engineering Inc. (BGC 2008a) is the most reliable MCF relationship currently available for Cheekye Fan. The portion of that MCF curve, representing smaller volume rainfall/surface water runoff-generated *debris flows*, is credible and could be a basis for considering debris flow mitigation strategies for this range of events. A spectrum of still smaller *debris floods* or stream floods should also be considered in mitigation strategies.

The 10,000-year return period landslide

The estimated volume of the 10,000-year return period debris flow that could reach Cheekye Fan is 5.5 million m³. This estimate is more conservative than that recommended by BGC (2008a), but is consistent with several other previous estimates. The 10,000-year return period landslide, which is conceptually comparable to a 'maximum credible earthquake' or a 'probable maximum flood', is the appropriate extreme event for estimating the largest debris flow that could affect Cheekye Fan.

Possible effects of climate change on future landslides

Climate change will increase the frequency of debris flows and debris floods of all sizes. This will have the effect of increasing the volumes of given-year events, including the 10,000-year return period landslide. However, it is not possible at present to quantify with certainty changes in the frequency of future debris flows due to climate change. Consequently, possible climate change effects must be considered by selecting suitably conservative parameters during the design of any mitigation, and by selecting solutions that are flexible with respect to the magnitude of potential effects.

Other Considerations

Risks from debris flows, debris floods, and stream floods to existing development on Cheekye Fan and area should be mitigated whether or not there is any future development on Cheekye Fan. With respect to mitigation of those risks to existing development and to possibly allow some new development, all forms of mitigation, singly or in combination, should be considered and carefully evaluated.

The Panel #1 report was accepted by all parties.

In February 2015, the District of Squamish sought additional information to address new development applications on Cheekye Fan while it was considering risk mitigation strategies. Two key factors the District wished to consider were³:

- a) Public safety: ensuring new development and work on existing homes is safe for the intended use by considering the best hazard [probability] information available.
- b) Ensuring potential fan-wide risk mitigation options (including relocation) are not further constrained by adding people and/or significant investment in areas requiring mitigation. Adding people increases risk, thereby increasing the protective requirements needed to lower that risk to an acceptable level."

In early March 2015, the District of Squamish approved actions related to hazards on the fan, including evaluating debris flow mitigation to reduce risk to existing development and possibly

³ District of Squamish Council Meeting, March 24, 2015.

allow for some new development, engaging the community, and establishing landslide risk tolerance criteria.

Later in March 2015, in response to a request from the District of Squamish for additional advice on these issues, the Province of BC, Squamish First Nation and its Partnership, and District of Squamish selected and appointed Panel #2 to advise on landslide risk tolerance criteria for existing and proposed new development on Cheekye Fan. Panel #2 consisted of the three members from Panel #1 plus one new member, Dr. Norbert Morgenstern P.Eng. Dr. John Clague was appointed Chair of Panel #2.

The following are the terms of reference for Panel #2, as agreed to by the Province of BC, Squamish Nation and its Partnership, District of Squamish, and Panel #2:

“The Panel will utilize the recommendations of the earlier “Cheekye River and Fan Expert Review Panel” [Panel #1] with respect to the frequency and magnitude of the debris flows being considered on the Cheekye Fan, and further review scientific and engineering reports and other risk tolerance criteria information provided by the Province, the District of Squamish and the Squamish Nation and its Partnership. This will not preclude the Panel, at its discretion, to review additional information that is otherwise accessible and relevant for its findings.

The Panel will assist *stakeholders* in:

- [Task 1] advising on risk tolerance criteria for existing and proposed new development on Cheekye Fan based on criteria adopted by other municipal, regional, and provincial agencies in British Columbia and/or elsewhere;
- [Task 2] advising on current levels of individual and group risk on Cheekye Fan for landslides/debris flows/debris floods;
- [Task 3] advising on individual and group risk reduction that might be achieved, given current and proposed new development, through remediation; and
- [Task 4] advising on whether group and individual risk tolerance criteria are best applied to landslides/debris flows/debris floods across the municipality or solely to the Cheekye Fan area.”

A complete version of the terms of reference is provided in Appendix A. Based on the above tasks, the focus of Panel #2 was on risk to life.

1.2 Panel #2 Process

Panel #2 was selected and appointed in late March 2015. Subsequently, a Steering Committee was formed from representatives of the Province of BC, Squamish Nation and its Partnership, and District of Squamish, to which Panel #2 reported. The Steering Committee consisted of:

- Mr. Dirk Nyland, P.Eng., Chief Engineer and Deputy Inspector of Dikes, Ministry of Transportation and Infrastructure
- Mr. Gary Buxton, General Manager of Development Services and Public Works, District of Squamish
- Chief Dale Harry, Squamish Nation
- Ms. Jennifer Chancey, P.Eng., Bethel Lands Corporation

Mr. Darren Stadel (BC Ministry of Jobs, Tourism and Skills Training) was appointed by the Steering Committee as Project Manager.

Panel #2 met with representatives of the Province of BC, Squamish Nation and its Partnership, and District of Squamish in late March 2015 to discuss the issues and finalize the terms of reference. All requested information related to existing and proposed development associated with the Cheekye River and Fan was provided to Panel #2 by late April 2015.

From published documents and personal contacts, Panel #2 determined what landslide risk tolerance criteria are currently being used elsewhere in the world. After reviewing this information as well as the information provided by the Province of BC, Squamish Nation and its Partnership, and District of Squamish, Panel #2 formulated its consensual opinions.

In May 2015, Panel #2 submitted several draft reports to the Steering Committee for review and comments, and met with the Steering Committee once.

Panel #2 acknowledges the assistance it received from the Steering Committee, others in their respective organizations, and Mr. Darren Stadel.

1.3 Report

This report is organized as follows:

The Executive Summary provides a summary of this report and Panel #2's opinions, and recommendations. Reference is made in the Executive Summary to specific sections of the body of this report that provide further background information.

- Section 2 provides a review of the Cheekye River watershed and Cheekye Fan, specifically their geography, geology, existing and proposed development, and previous studies, research, and publications. Much of this section has been abstracted from the Panel #1 report.
- Section 3 provides background to risk and risk assessment and to the terminology used in such assessments as they relate to landslides.
- Section 4 provides a review of the development of risk tolerance criteria around the world, from the industrial and nuclear engineering fields, to dam safety, to landslides. It also addresses landslide *hazard probability tolerance criteria*.
- Section 5 addresses Tasks 1 and 4 undertaken by Panel #2: landslide risk tolerance criteria for Cheekye Fan and whether these criteria can be applied to the entire District of Squamish.
- Section 6 addresses Tasks 2 and 3 undertaken by Panel #2: the existing individual and societal risk from landslides on Cheekye Fan and how risk reduction to existing and proposed new development might be achieved by mitigation.

References and a Glossary of important technical terms used in this report follow Section 6. Appendix A is the terms of reference and Appendix B includes the curriculum vita of each Panel #2 member.

1.4 Limitations

This report is based entirely on available reports and publications reviewed by Panel #1, additional information gathered and received by Panel #2, and the collective experience of the individual Panel #2 members. No new studies were carried out as part of this work.

The information, advice, and recommendations presented in this report reflect the opinions of Panel #2 based on the information available to it at the time this report was prepared. Panel #2 carried out its review and prepared this report in a manner consistent with the level of care and skill exercised by geological and engineering professionals currently practicing in BC.

It is emphasized that Panel #2's advice and recommendations with respect to landslide risk tolerance criteria provide a starting point for stakeholders and jurisdictional decision-makers to evaluate landslide risk on Cheekye Fan. As will be stated again in this report, experienced engineers and geologists can provide valuable input and informed advice for determining landslide risk tolerance criteria, but stakeholders and jurisdictional decision-makers ultimately have to select by means of an appropriate public process the appropriate risk evaluation parameters for a particular situation or jurisdiction.

This report is for the sole use of the Province of BC, Squamish Nation and its Partnership, and District of Squamish. Any use that a Third Party makes of this report, or any reliance or decisions based on this report, is the sole responsibility of those Third Parties. Panel #2 accepts no responsibility for damages or injury of any sort or extent, if any, suffered by any Third Party as a result of information in this report or decisions made based on information in this report.

Section 2: Setting, Development and Previous Studies

The section provides a review of the Cheekye River watershed and Cheekye Fan, specifically their geography, geology, existing and proposed development, and previous studies, research, and publications.

2.1 Cheekye River Watershed

The Cheekye River watershed has an area of approximately 60 km². The river flows westward approximately 13 km from the west flank of Mount Garibaldi and the Garibaldi glacier complex (approximate elevation 2700 m asl⁴) into Cheakamus River (approximate elevation 50 m), and then into Squamish River approximately 3 km downstream from the Cheekye/Cheakamus river confluence (Figures 1 and 2).

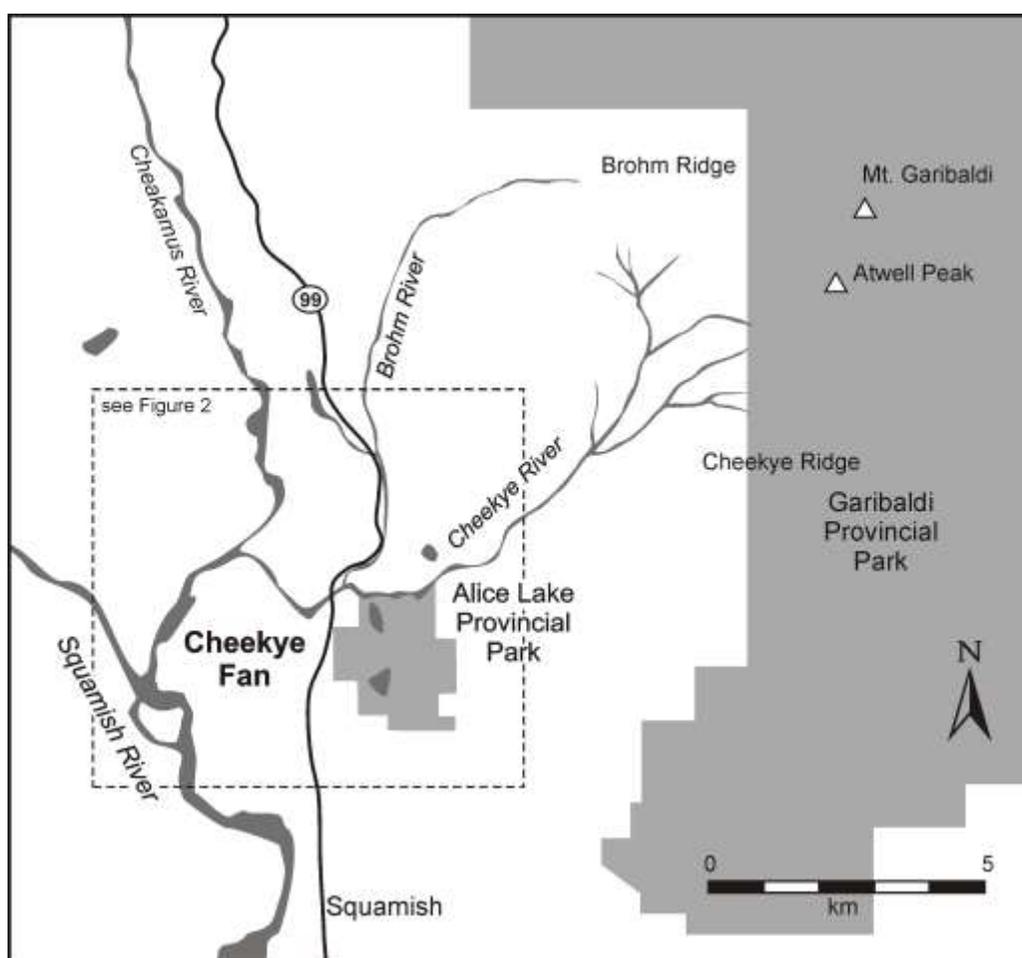


Figure 1: Location map showing the Cheekye and Brohm river watersheds and Cheekye Fan.

⁴ Above sea level. All elevations in this report are elevations above sea level.

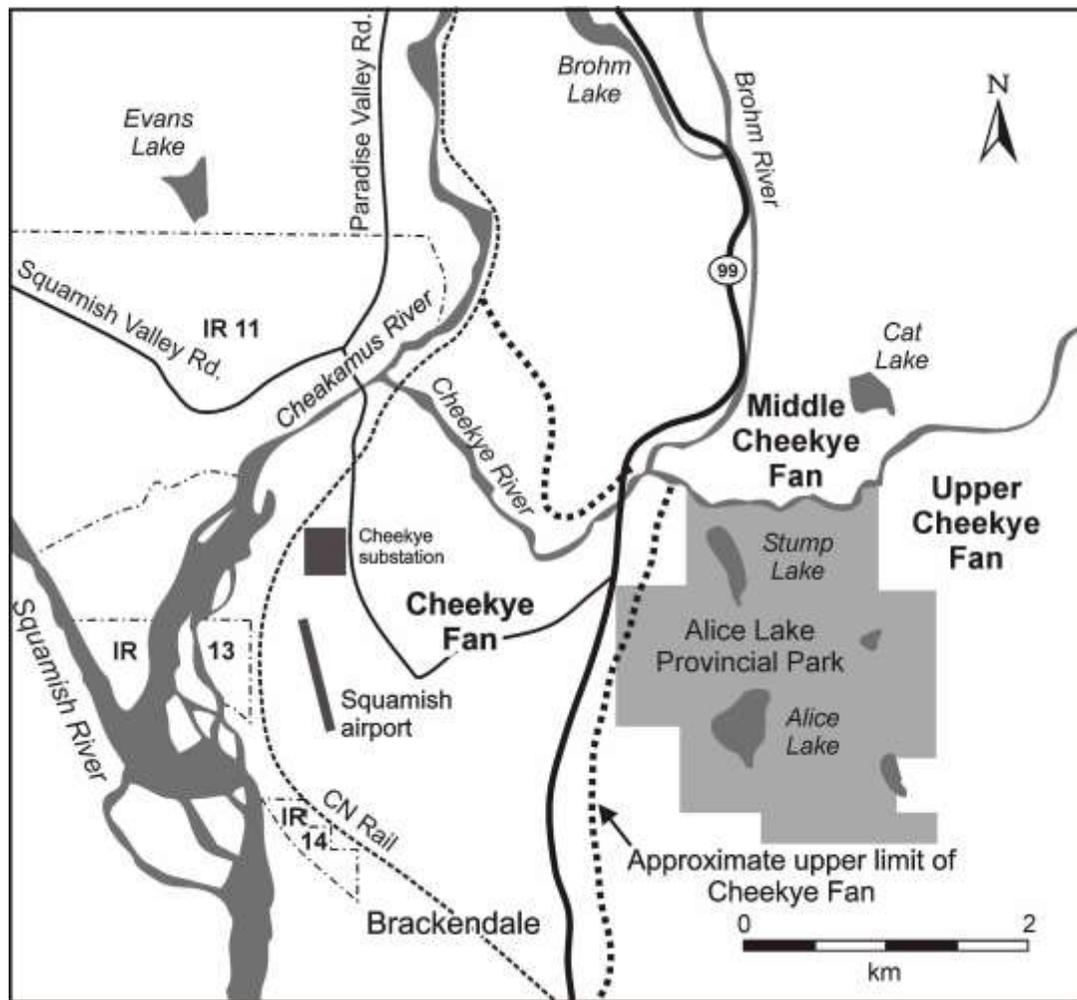


Figure 2: Map of the lower Cheekye River and Cheekye Fan.

The Cheekye River watershed drains an amphitheatre-shaped headwater area that includes, from north to south, Brohm Ridge, Mount Garibaldi, Atwell Peak, and Cheekye Ridge. The headwater slopes are very steep – up to 45° on average, over a distance of 1-2 km from the highest points in the watershed. The main tributaries, with the exception of Brohm River, enter the main stem of the river above an elevation of approximately 500 m, approximately 8.5 km from the head of the basin.

Cheekye River then flows across approximately 2.5 km of hummocky terrain that contains a number of small lakes. Mathews (1952, 1958) referred to this hummocky terrain as the ‘Upper’ and ‘Middle’ Cheekye fans (Figure 2 of this report) and showed that they developed, in part, from thick volcanic debris (*pyroclastic deposits* and lava flows) that collapsed from the west flank of the then-active Mount Garibaldi volcano about 13,000 years ago, and were deposited on melting glacier ice that filled the lower Cheakamus and Squamish valleys at that time. This hummocky terrain was subsequently incised, reworked, and redeposited, with additional material from the headwaters, to form ‘Lower’ Cheekye Fan.

2.2 Lower Cheekye Fan (Cheekye Fan)

Lower Cheekye Fan (or simply Cheekye Fan, Figure 2) is a type of fan, common to high mountainous regions, that has been formed over many millennia by natural alluvial sedimentation as well as by deposition of episodic debris flows and debris floods. *Natural hazards* that occur on this type of fan include stream floods, deposition of sediment, erosion of new channels, *avulsions*, debris floods, debris flows, and possibly other types of landslides.

Cheekye Fan extends from its apex, approximately 0.5 km upstream of BC Highway 99, (approximate elevation 150 m) downstream approximately 3.5 km to Cheakamus River on the north and to Squamish River to the south. The present course of Cheekye River changes abruptly from southwest to northwest approximately 1 km downstream of the fan apex. This point is commonly referred to in consulting reports as the Cheekye River 'dogleg'.

Brohm River is the main northern tributary of Cheekye River and has a watershed area of approximately 16 km². It enters Cheekye River downstream of the apex of Cheekye Fan, just upstream of the BC Highway 99/Cheekye River bridge. Its headwaters are in the area north of Brohm Ridge (approximate elevation 1700 m), and its watershed includes Brohm Lake on the west side of BC Highway 99 (Figures 1 and 2).

Cheekye Fan has an approximate area of 7 km² and an average gradient of approximately 2.5°. The fan is bordered by Cheakamus River on the west and grades onto the Squamish River floodplain on the south. Cheakamus and Squamish rivers are eroding the western distal margins of the fan.

2.3 Existing and Proposed Development

Part of the community of Brackendale is located on the southwest flank of Cheekye Fan (Figure 2). A number of rural residences, the BC Hydro Cheekye substation and associated transmission lines, the Squamish Airport, and some light industry are also located on the fan. BC Highway 99, a number of main and subdivision roads, and the CN Rail (the former BC Rail) line cross the fan.

Three Skwxwú7mesh villages are located on or near the western distal margins of Cheekye Fan (Figure 2):

- IR#11 Ch'iyakmesh and the associated village are located on the west side of Cheakamus River immediately opposite the Cheekye/Cheakamus river confluence;
- IR#13 Pukwayusem and Skemin, which is currently uninhabited, straddle the mouth of Cheakamus River immediately upstream from the Cheakamus/Squamish river confluence; and
- IR#14 Wiwk'em and the associated village are located northwest of Brackendale.

There has been a modest amount of new residential development on portions of Cheekye Fan over the past 15 years. This development has not been concentrated in any one area (District of Squamish, personal communication, 2015).

Over the years, there have been several proposals to expand residential development on Cheekye Fan, the most recent of which is the 2014 proposal by Squamish Nation and its Partnership for a 750 lot residential development located southeast of the Squamish Airport (see Figure 2) and north and east of the Don Ross Secondary School and the Brackendale Elementary School.

The current District of Squamish Official Community Plan (OCP), Bylaw 2100, was adopted in 2009 (District of Squamish 2009). With regard to Brackendale, and to Cheekye Fan in general, development is guided by the 1993 Thurber Engineering Ltd. and Golder Associates Ltd. 'Cheekye River Terrain Hazard and Land Use Study' (TEL-GAL 1993) that estimated the magnitude, frequency, and likely areal extent of debris flows originating from the Cheekye River watershed. TEL-GAL used these estimates to delineate six 'Hazard Zones' (four from debris flows; two from steam flooding); within each zone, the severity of the hazards would be relatively consistent. Figure 3 of this report is a portion of Schedule D1 of Bylaw 2100 (District of Squamish 2009). With regard to the four debris flow hazard zones, the bylaw states that:

- zones 1 or 2 "are not suitable for land subdivision or permanent buildings and structures",
- building development will only be allowed in zones 3 or 4 and require a) "a Debris Flow Management Plan; and b) implementation of appropriate mitigation measures".

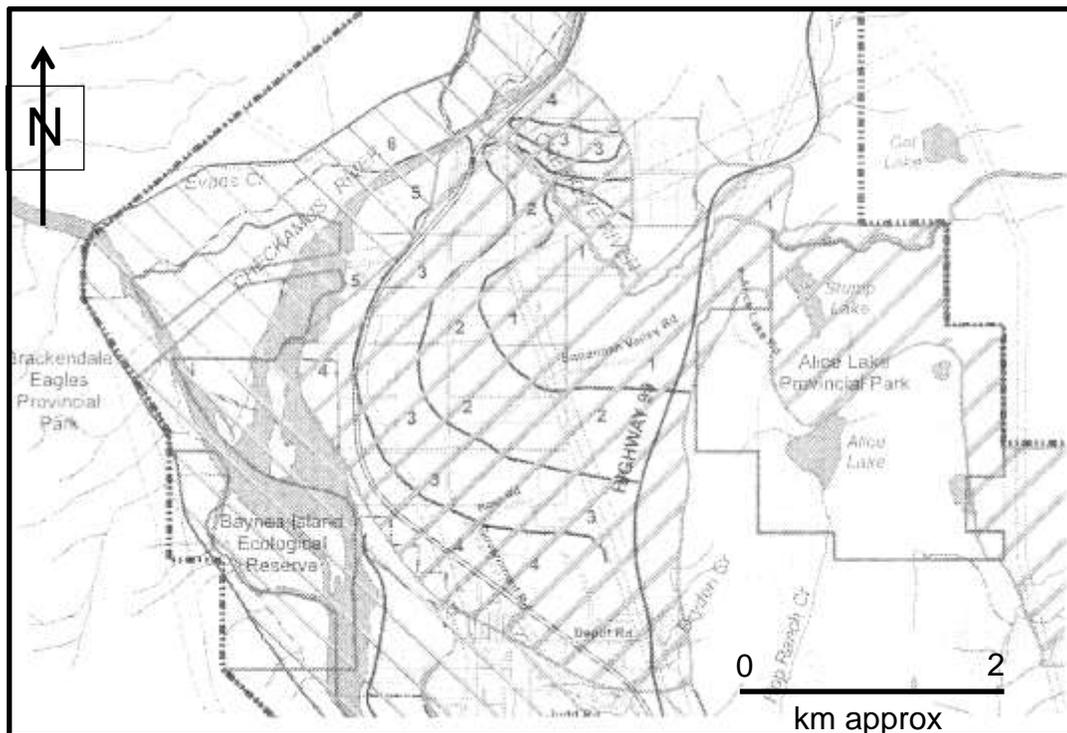


Figure 3: Portion of District of Squamish OCP, Bylaw 2100, Schedule D1, showing 'Hazard Zones' on Cheekye Fan derived from TEL-GAL (1993) and District of Squamish (2009).

The residential development proposed by the Squamish Nation and its Partnership would require an OCP amendment to change the land-use from 'Restricted Industrial' to 'Residential', and a "debris flow management plan and safety certification by a Qualified Professional" (District of Squamish, personal communication, 2015).

2.4 Previous Studies, Research, and Publications

As previously mentioned, the first research on the Cheekye River watershed and Cheekye Fan dates back to the 1940s, when W.H. Mathews, then a geological PhD student and later a professor of geology at the University of British Columbia, conducted his pioneering work in Garibaldi Park (Mathews 1952, 1958). A debris flow that reached and impacted Cheekye Fan in 1958 was investigated and documented by a geologist with the BC Department of Mines (Jones 1959).

In the mid-1970s and early 1980s, the geotechnical engineering consulting firm Crippen Engineering Ltd.⁵ carried out several investigations for the BC Department of Housing and the BC Ministry of Lands, Parks and Housing (Crippen 1974, 1975, 1981). It studied the landslide hazards and risks in the Cheekye River watershed and on Cheekye Fan, and proposed mitigation of such hazards and risks for the purpose of developing portions of the fan.

In the 1980s and early 1990s, Mr. Frank Baumann P.Eng., a consulting geological engineer in Squamish, carried out a number of studies on the extent and age of several prehistoric debris flows on Cheekye Fan (Baumann 1991).

In the early 1990s, Thurber Engineering Ltd. and Golder Associates Ltd., two geotechnical engineering consulting firms, jointly carried out a comprehensive geological hazard and risk study of the entire Cheekye River watershed and Cheekye Fan (TEL-GAL 1993). This study was commissioned by the BC Ministry of Environment, Lands and Parks in response to Baumann's findings, new development proposals, and a review of all available information by G.C. Morgan P.Eng., a consultant to the BC Ministry of Environment (Morgan 1991). The co-authors of the TEL-GAL study subsequently published two technical papers on the investigation, the techniques used, and the results (Hung and Rawlings 1995; Sobkowicz et al. 1995).

In the late 1990 and early 2000s, a number of geoscientists studied different aspects of the geologic history of Cheekye Fan. The results of these studies were published in a number of scientific papers (Friele et al. 1999; Ekes and Hickin 2001; Friele and Clague 2002a, 2002b, 2005, 2009; Clague et al. 2003; Ekes and Friele 2003).

In 2003, the BC Ministry of Water, Lands and Air Protection retained Kerr Wood Leidal Associates Ltd., a water-resource engineering consulting firm to evaluate Cheekye Fan dike options in light of the TEL-GAL (1993) conclusions (KWL 2003).

⁵ Now a part of the consulting firm Kohn Crippen Berger Ltd.

In 2007, KWL investigated and developed stream flood and debris flow mitigation strategies for Cheekye Fan on behalf of the Cheekye River Development Limited Partnership (Squamish Nation and MacDonald Development Corporation) (KWL 2007). Also in that year and in 2008, BGC Engineering Inc., a geological engineering consulting firm, completed a comprehensive landslide and debris flow hazard and risk study of the Cheekye River watershed and Cheekye Fan (BGC 2007, 2008a, 2008b). This study was carried out for KWL and its client, the Cheekye River Development Limited Partnership. The studies carried out by KWL and BGC, and the resulting conclusions were reviewed and approved by a Cheekye Fan Geotechnical Review Board (CFGRB) for the MacDonald Development Corporation. The CFGRB consisted of Dr. Norbert Morgenstern P.Eng., Dr. Oldrich Hungr P.Eng./P.Geo., and Dr. Andrew Robertson P.Eng. (Cheekye Fan Geotechnical Review Board 2007, 2008a, 2008b). Published technical papers resulting from BGC's studies include Jakob and Friele (2010) and Jakob et al. (2012).

In 2012, Golder Associates Ltd. was retained by the BC Ministry of Forests, Lands and Natural Resource Operations to review the earlier studies and research. Specifically it reviewed the 2007 and 2008 studies by KWL and BGC, and provided its opinion on the conclusions reached by KWL and BGC with respect to landslide and debris flow hazards and risks in the Cheekye River watershed and on Cheekye Fan (Golder Associates 2013).

Section 3: Background to Risk and Risk Assessment

This section provides some background on risk, risk assessment, and the terminology used in such assessments related to landslides.

3.1 Risk Management

In 2009, the International Organization for Standardization (ISO) released a generic guidance document on the management of risk (ISO 2009). The guidance is not specific to any country, industry, or sector and is intended for use by any public, private, or community group, or individual. In 2010, the Canadian Standards Association (CSA) adopted ISO (2009) as its national standard for managing risk (CSA 2010a) and also published a draft companion guidance document (CSA 2010b). Neither of these documents is specific to landslides.

Figure 4 shows the generic risk management process as described in ISO (2009), adapted specifically to Canadian landslide risk management including landslide risk assessment (VanDine 2012).

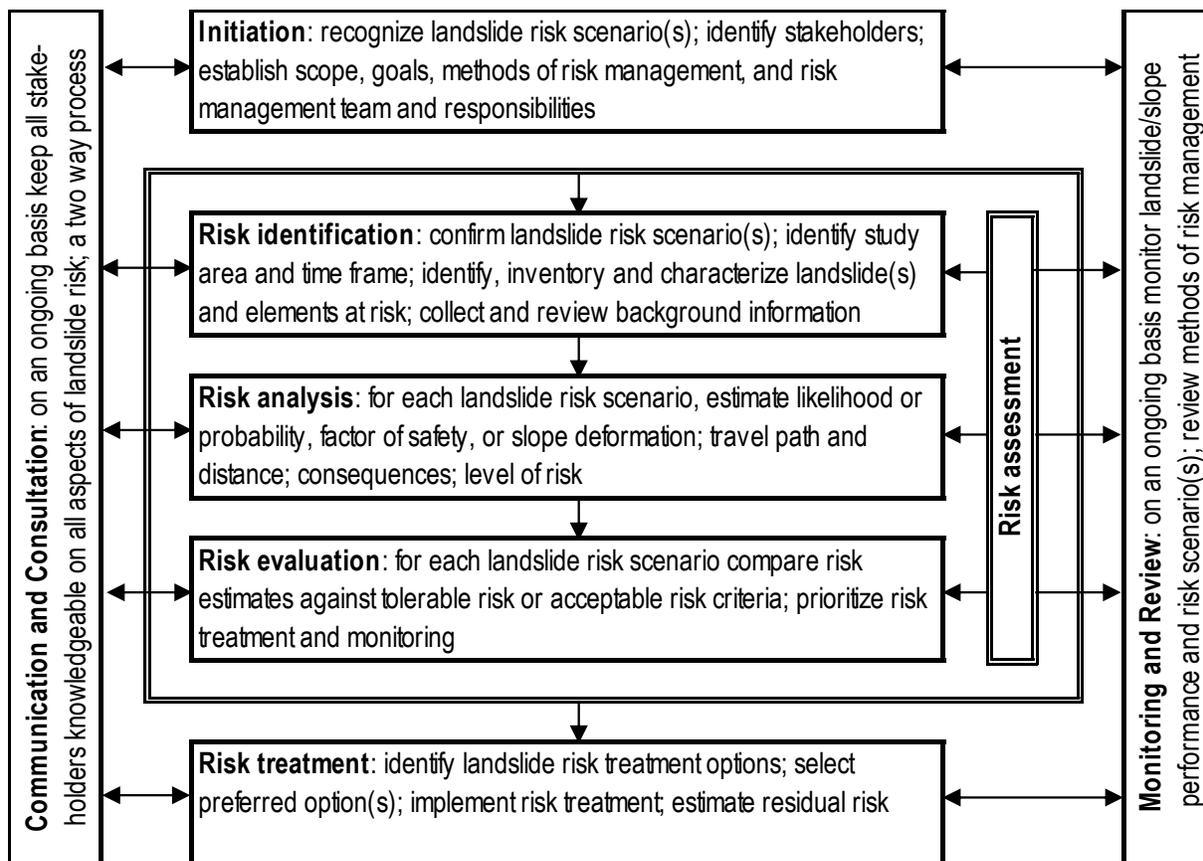


Figure 4: Landslide risk management process (from VanDine 2012, adapted from ISO 2009).

As shown in Figure 4, landslide risk management involves seven tasks: initiation, risk identification, risk analysis, risk evaluation, risk treatment (mitigation), communication and consultation, and monitoring and review.

The double outlined box in Figure 4 delineates landslide risk assessment and is composed of three of the seven risk management tasks:

- risk identification: identification or confirmation of risk scenarios;
 - risk analysis: estimation of the landslide risk by combining i) the hazard probability (likelihood or probability of occurrence of a landslide) and ii) the resulting consequences; and
 - risk evaluation: comparison of the estimated risks to established *tolerable risk* (or *acceptable risk*) criteria;
- where:
- tolerable risk is a range of risk that society can live with to gain certain net benefits, with the caveat that this range of risk must be reviewed and reduced if possible; and
 - acceptable risk is a risk that society is prepared to accept and for which no risk mitigation is required.

3.2 Landslide Risk

Mathematically, landslide risk can be expressed as:

$$R = P_H \times C \quad \text{[Equation 1]}$$

where:

- R is the risk,
- P_H is the probability of a landslide occurring (hazard probability), and
- C is the *consequence*.

Consequence depends on whether the landslide reaches a particular location, whether there are any elements at risk at that location, and how likely those elements are to be damaged.

Elements at risk include human health and safety, property, the environment, and/or financial interests. In western society, human health and safety typically take precedence over all other elements. As an example, the Swiss Federal Office of the Environment (OFEFP 1996) listed the following hierarchy of elements at risk relating to industrial activities:

- human life,
- personal injury,
- surface water pollution,
- groundwater pollution,
- agricultural land usability, and
- material losses.

For the purpose of this review, which is related to landslides and to existing and proposed residential development, human life is considered the prime element at risk. This consideration is consistent with the land-use development approval process in Hong Kong, Australia, and the District of North Vancouver, and industrial health and safety regulations in the United Kingdom, the Netherlands, and elsewhere (Porter and Morgenstern 2013).

An important consideration for landslide risk assessment is whether the risk is voluntary (within one's control, for example, sky diving) or involuntary (considered to be outside of one's control, for example, being struck by lightning). Risks from landslides in residential areas are typically considered involuntary risks. Society has a lower tolerance for involuntary risks than voluntary risks.

A landslide risk assessment must also consider whether one individual is likely to be affected by the event (*individual risk*) or multiple individuals (*group risk* or *societal risk*):

"When the area of a potential landslide is small and the density of development is low, approval decisions are typically governed by the estimated individual risk. In contrast, when large groups are exposed to a potential landslide, societal risk analysis is typically used." (Porter and Morgenstern 2013)

Landslide risk assessments can be qualitative or quantitative. A qualitative risk assessment compares risks in relative terms, such as low, moderate, and high. A *quantitative risk assessment* uses numerical values or ranges of values. Development of quantitative risk assessments began in the 1970s, primarily in the field of industrial and nuclear engineering (AICE 1989). The application of such assessments to landslides is relatively new and still developing (for example, see Morgenstern 1995 and APEGBC 2012). The primary function of a quantitative risk assessment is to communicate the results of a risk assessment in quantitative terms. Although efforts are made to express the risk in objective terms, some numerical values used in quantitative risk assessment may be determined by subjective judgment (Vick 2002).

Macciotta (2013) summarizes the advantages of quantitative risk assessments in connection with landslides:

- the ability to present assessment results in absolute, rather than relative, terms;
- provision of better cost comparisons of proposed mitigation strategies as a function of associated risk reductions; and
- provision of more objective and transparent decisions that can be shared with regulators, stakeholders, and society.

For quantitative assessments, landslide risk is typically expressed in terms of annual probability. The risk with respect to loss of life from a landslide is: the annual probability that a landslide will occur, that it will reach a particular location, that a person will be at that particular location, and that the landslide will be large enough or sufficiently fast to cause death. The capability of a landslide to cause death depends on the character of the landslide (for example, flow depth and velocity) and the character of the individual's immediate surroundings (for example, an open field, inside a building, or behind a large barrier).

Equation 1 can be expanded to show landslide risk as a product of the following terms:

$$R = P_H \times P_{S:H} \times P_{T:S} \times V \times E \quad \text{[Equation 2]}$$

where:

- R is the risk,
- P_H is the annual hazard probability (probability of a landslide occurring),
- $P_{S:H}$ is the spatial probability (probability of the landslide reaching a particular location),
- $P_{T:S}$ is the temporal probability (probability of an individual being at that location when the landslide occurs),
- V is the vulnerability (probability of loss of life if an individual is impacted by the landslide), and
- E is the number of people at risk (equal to 1 for individual risk).

Comparing equations [1] and [2], consequence (C) = $P_{S:H} \times P_{T:S} \times V \times E$.

To estimate the total landslide risk to an individual (individual risk), the estimated risks from all significant landslides are added together. To estimate 'societal risk', more complex calculations are required.

Annual hazard probability is typically expressed in terms such as 1:1,000 (an example only). The term 1:1,000 is equivalent to $1/1,000$ or 0.001^6 , which means that on average over many years there is a $1/1,000$ or 0.001 probability of a landslide occurring in any given year⁷. An event, such as a landslide, with an annual hazard probability of 1:1,000 is often referred to as a 1,000-year *return period* event⁸. This does not mean that the event will ONLY occur once every 1,000 years. Therefore a 1,000-year return period event can occur this year, next year, or thousands of years from now.

Spatial probability, temporal probability, and vulnerability are typically expressed as values between 0 and 1; the former value has a zero probability of occurring, and the latter value has a 100% probability of occurring (that is, it is certain to occur).

When the different probabilities are multiplied together, the numerical value of risk becomes very small. For example, for a 1,000-year return period event (annual hazard probability = $1/1,000$ or 0.001) where spatial probability, temporal probabilities, and vulnerability are all 0.5 (a 50-50 chance), the annual risk to life of the most-exposed individual ($E = 1$) from that landslide would be:

⁶ Scientifically, a small value such as 1:1,000, $1/1,000$ and 0.001 is referred to as 10^{-3} ; similarly 1:10,000 (10^{-4}), 1:100,000 (10^{-5}) and 1:1,000,000 (10^{-6}) etc. This report refers to all risks in the format similar to '1:1,000'.

⁷ The number 0.001 is between 0 (indicating there is zero chance that a landslide will occur in any given year) and 1 (indicating a landslide is certain to occur in any given year).

⁸ This report refers to all hazard probabilities in the format similar to 'xxxx-year return period event', for example '1,000-year return period event'.

$$P_H \times P_{S:H} \times P_{T:S} \times V \times E = R$$

$$0.001 \times 0.5 \times 0.5 \times 0.5 \times 1 = 0.000125 \text{ or } 1/8,000 \text{ or } 1:8,000$$

To better communicate low probabilities and risks, they can be expressed as a 'x'% probability or risk of at least one occurrence in 50 years. For example, an annual probability or risk of 1:500 is approximately equivalent to 10% in 50 years; 1:1,000 is 5% in 50 years; 1:2,500 is 2% in 50 years; 1:5,000 is 1% in 50 years; and 1:10,000 is 0.5% in 50 years.

3.3 Living with Landslide Risk

Both the probability of, and the risks from, a landslide are greater in mountainous areas than elsewhere. Small landslides occur frequently; large landslides occur much less frequently but can travel longer distances and potentially reach developed areas on fans and valley floors. In order to live in mountainous areas, individuals and society must be prepared to tolerate some risks from landslides. It is not practical to reduce these landslide risks to zero.

Life, in general, requires some tolerance of risk. For example, between 2009 and 2013 there was an average of 314 road accident fatalities in BC each year (Insurance Corporation of British Columbia website⁹). Dividing 314 by the population of the province (4.6 million), the risk of a citizen dying from a road accident (individual risk) is 1:10,000 each year. To avoid this risk, an individual can choose to not drive or be a passenger in a vehicle. Because of the substantial inconvenience of not driving or being a passenger, however, most individuals tolerate this risk.

For comparison, examples of an individual's annual risk of dying from other everyday voluntary activities are: smoking (1:200), canoeing (1:500), and skiing (1:10,000 for 100 hrs/year). Similarly, examples of an individual's annual risk of dying from everyday involuntary causes are: electrocution (1:65,000), wildlife-related collisions in BC (1:1,500,000 between the years 2000 to 2005) and lightning strikes (1:5,000,000) (adapted from Morgan 1992, Porter and Morgenstern 2013, and Province of BC, personal communication, 2015).

Society's risk tolerance decreases with larger accidents. For example, most BC citizens would find it intolerable if each year a plane with 314 persons on board (the same number of individuals that die on average every year in BC road accidents) crashed somewhere in the province. For this reason, 'individual risk' and 'societal risk' are evaluated separately.

3.4 F-N Diagram

Societal risk can be expressed by plotting the annual frequency (annual probability) of N or more fatalities (F) against the number of fatalities (N). The result is a F-N diagram¹⁰, where F increases logarithmically upward along the vertical axis and N increases logarithmically to the

⁹ <http://www.icbc.com/about-icbc/newsroom/Documents/fatal-victims.pdf>.

¹⁰ Technically, F-N diagrams for landslides should refer to annual probability, not annual frequency, but they are most commonly referred to as F-N diagrams, rather than the more technically correct P-N diagrams.

right along the horizontal axis. An example of a generic F-N diagram, without numerical values, is shown in Figure 5.

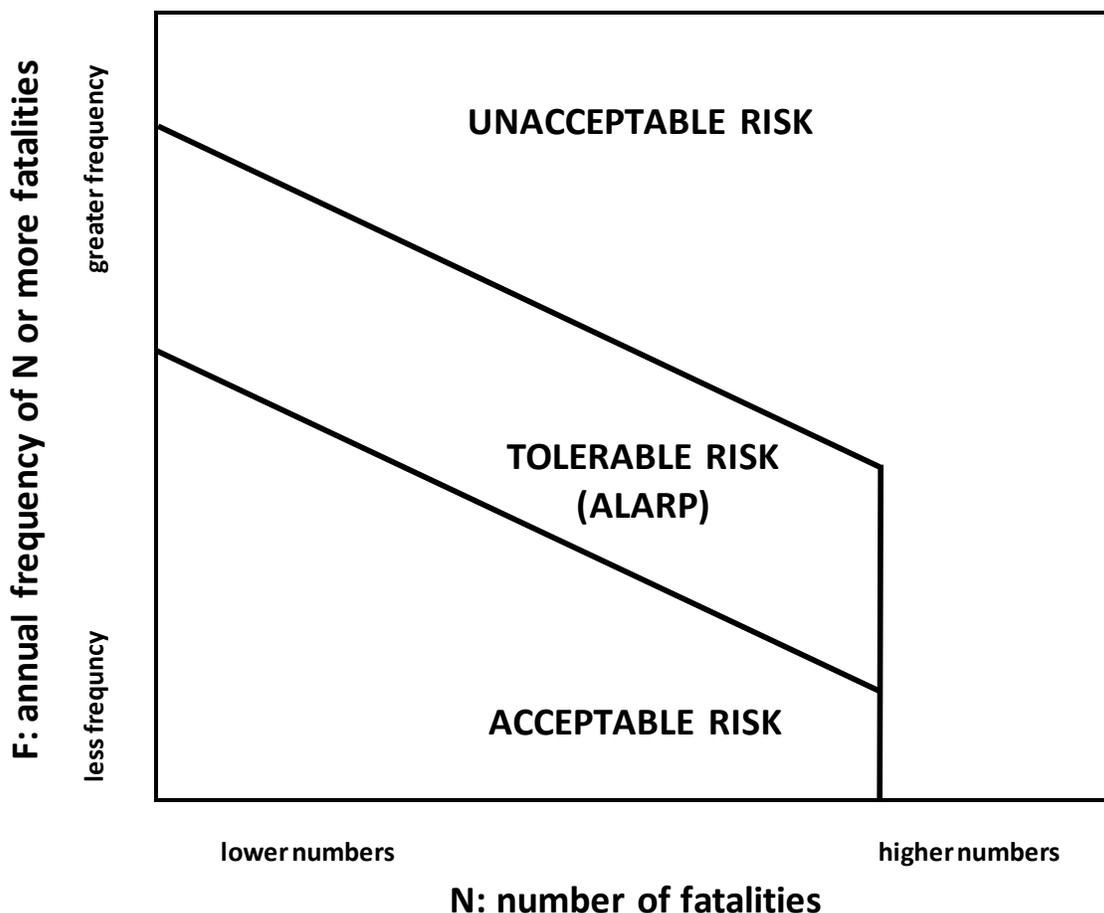


Figure 5: Generic F-N diagram.

Also shown on Figure 5 are three zones: unacceptable risk, tolerable risk, and acceptable risk. The lines sloping to the right indicate that society’s tolerance for risk decreases as the number of fatalities increases. The vertical line, which truncates both the tolerable and acceptable risk zones, indicates that there is a limit to the number of fatalities that society will accept, regardless of how small the risk.

The zone of tolerable risk is also referred to as ALARP (‘as low as reasonable practicable’). Society typically can live with risk in this zone to achieve certain net benefits, but the risk needs to be frequently reviewed and reduced if possible. Risks, however, can never be reduced to zero, and therefore there will always be some *residual risk*, even after risk reduction.

3.5 Landslide Risk Tolerance Criteria

As mentioned in Section 3.3 of this report, in order to live in mountainous areas, individuals and society must be prepared to tolerate some risks from landslides. It is not practical to reduce these landslide risks to zero.

When referring to the specific person who is most exposed to risk, individual risk is termed 'personal individual risk' (PIR), and the corresponding risk tolerance criterion is typically a single number. Landslide risk tolerance is generally less for an individual in a new residential development than for an individual in an existing residential development. Societal risk tolerance criteria are typically expressed as a F-N diagram as explained in Section 3.4 of this report. Societal risk includes risk to both existing and new residential development, and therefore there is only a single F-N diagram for societal risk.

With regard to determining landslide risk tolerance criteria, Porter and Morgenstern (2013) state:

"While landslide [risk tolerance] criteria may vary amongst jurisdictions and the criteria for individual and societal risk are different, some common general principles apply (Leroi et al, 2005):

- the risk from a landslide to an individual should not be significant when compared to other risks to which a person is exposed in everyday life;
- the [societal] risk from a landslide should be reduced wherever reasonably practicable; that is, the ALARP principle should apply;
- 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 landslide safety criteria; and
- higher risks are likely to be tolerated or accepted for existing developments than for proposed developments."

A number of jurisdictions have established tolerance criteria for landslide risks or landslide hazard probabilities, as described in Section 4 of this report. As mentioned in Section 1.4 of this report, engineers and geologists can provide valuable input for determining landslide risk tolerance criteria. However, stakeholders and jurisdictional decision-makers ultimately have to select, by means of an appropriate public process, the appropriate risk evaluation parameters (hazard probability, and landslide volume and/or peak discharge) for a particular situation or jurisdiction. This selection has to balance the risks from landslides with societal values. Societal values include things such as public safety, affordable residential land, and return on investment.

Once landslide risk or hazard probability tolerance criteria have been established and appropriate risk evaluation parameters have been selected, communities can choose a number of options or a combination of options to meet the criteria. Communities can choose, for example, not to develop areas that could be affected by landslides, they can choose to construct some form of engineered mitigation structure, or they can choose a combination of options. Such choices reduce the risks, and the principle of reducing risks to a level 'as low as reasonably practicable' is referred to as the ALARP principle.

Section 4: Landslide Risk Tolerance Criteria

As discussed in Section 3 of this report, risk evaluation involves comparison of the estimated risks to established risk tolerance criteria. Also as mentioned in Section 3, the development of quantitative risk assessments began in the 1970s in disciplines other than landslides and has slowly been adapted to landslide risk management. This section provides a review of the development of risk tolerance criteria throughout the world, from the industrial and nuclear engineering fields, to dam safety, to landslides.

Because quantitative risk assessment is a relatively new concept in landslide risk management, most jurisdictions around the world still base landslide management on hazard probability rather than risk (Hungr 1997). This section, therefore, also reviews landslide hazard probability tolerance criteria.

Although the literature on hazard probability tolerance criteria and risk tolerance criteria is extensive, much of it is associated with proposals by researchers or academic groups that have little or no legal or regulatory status. There are only a few examples of tolerance criteria that have been translated into binding land-use regulations, particularly for landslides.

4.1 Risk Tolerance Criteria: Industrial and Nuclear Engineering

The United Kingdom Health and Safety Executive (HSE) began to consider risk tolerance criteria for industrial accidents in 1974 (HSE 2001). The first risk criteria developed were those for individual risk. The criteria were based on the assumption that risk imposed involuntarily on an individual due to construction of an industrial facility should be significantly lower than background risks from other causes. It was estimated that the lowest natural individual probability of death of a young child in a developed country is of the order of 1:10,000 per year and the comparable risk for an average adult is roughly 10 times greater. Therefore, for imposed risks to be significantly lower, the HSE specified risk tolerance criteria of 1:10,000 to 1:100,000 per year (HSE 2001). The HSE also considered that certain voluntary risks, such as those taken by workers in dangerous environments, could be tolerated up to a level of 1:1,000.

As mentioned in Section 3.2 of this report, society is more averse to risks faced by groups of individuals than to risks to individuals alone. After a lengthy period of development, HSE adopted a F-N diagram for risk tolerance criteria related to industrial activity (Figure 6 of this report). The upper sloping line, anchored by HSE at $F = 1:5,000$ and $N = 50$, represents the minimum limit of unacceptable risk. A second line, two orders of frequency lower, anchored at $F = 1:500,000$ and $N = 50$, represents the maximum limit of broadly acceptable risk. These anchor points are shown as dashed-dotted lines on Figure 6. Separating these two lines is a zone of intermediate risk, where application of the ALARP (as low as reasonably practicable) approach is recommended.

Some idea of the meaning of these lines can be obtained by noting that the lower inclined line in Figure 6 corresponds approximately to the line defining total risk to groups of people from all major accidents in United States during the 1970s (Rasmussen 1975). This heavy dashed

line on Figure 6 has been scaled to an exposed population of 1,000, a number that corresponds approximately to the population of a residential neighbourhood surrounding an industrial plant. In other words, the line separating the ALARP and broadly acceptable zones approximately coincides with the total risk to people from all major accidents in United States during the 1970s (background accident risk).

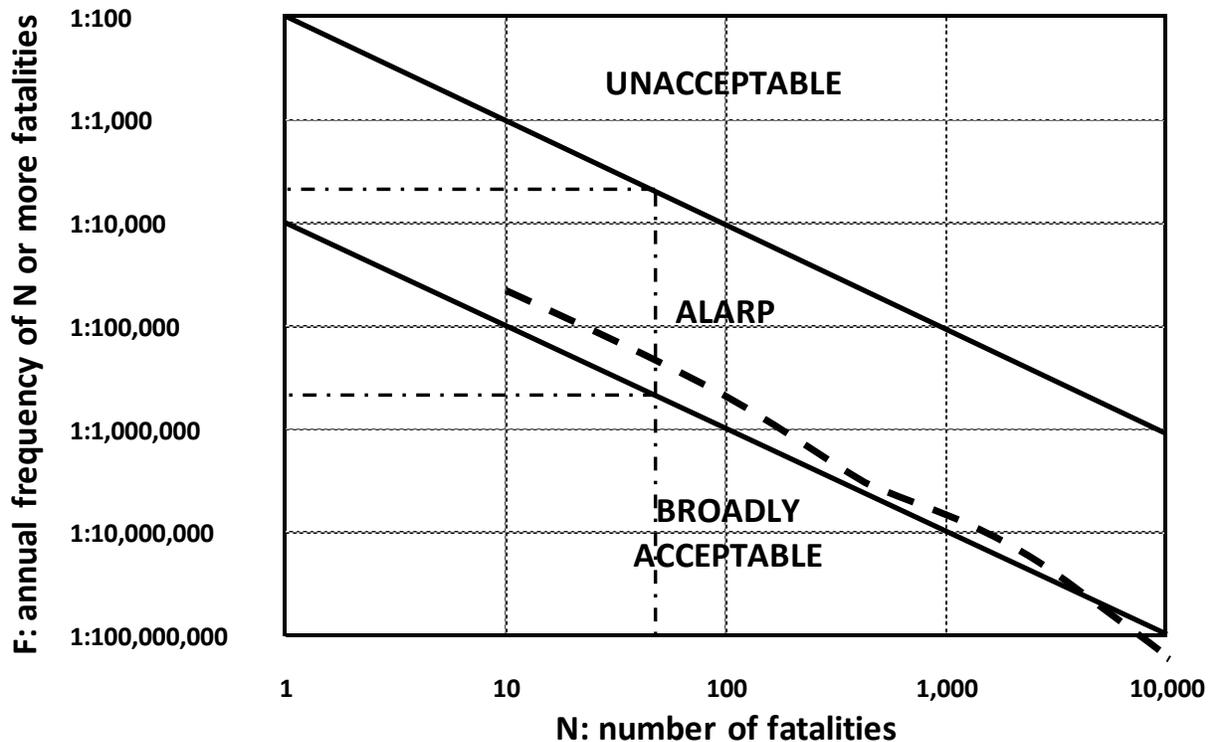


Figure 6: F-N diagram showing risk zones for industrial hazards (not landslides), as recommended by the United Kingdom Health and Safety Executive (adapted from HSE 2001). Overlain on this F-N diagram are dashed-dotted lines that represent HSE anchor points and an inclined heavy dashed line representing the total risk from all major accidents in the US during the 1970s (Ramussen 1975), scaled to an exposed population of 1,000. This F-N diagram has never been used for landslide risks.

The use of the ALARP principle was successfully defended in the British courts in 1949 (HSE 2001).

Within the ALARP zone:

“efforts to reduce risk should be continued until the incremental sacrifice (in terms of time, effort, cost or other expenditure of resources) is grossly disproportionate to the value of the incremental risk reduction achieved.” (AICE 1989).

Following disastrous flooding in 1953, the Netherlands adopted a limiting individual risk of 1:1,000,000 per year associated with sea dyke failures. Current industrial risks in the

Netherlands are regulated using a F-N diagram, anchored at the same point as in Figure 6, but sloping twice as steeply. The steeper slope reflects the strong aversion that Dutch society has for accidents that could claim large numbers of lives. These more conservative criteria have led to practical problems for industrial development in the Netherlands. They are maintained as guidelines, rather than mandatory standards (Ale 2005), and they have not been used in connection with landslides.

Other jurisdictions have defined similar risk tolerance criteria zones, in some cases more stringent than those shown in Figure 6 (for summaries, refer to AICE 1989 and Leroi et al. 2005). All of the criteria related to industrial risks are more conservative than the tolerance of risk from landslides.

In the early 1990s, the Hong Kong Government adopted risk tolerance criteria pertaining to 'potentially hazardous installations' that are one order of magnitude more conservative than the HSE criteria shown in Figure 6 (Malone 2005). This perhaps reflects Hong Kong's regional perspective on risk tolerance. Otherwise, the F-N diagrams from the United Kingdom and Hong Kong have the same slope, and the ALARP zones have the same width. As discussed in Section 4.3.1 of this report, the Hong Kong Geotechnical Engineering Office subsequently adopted the Hong Kong Government's 'potentially hazardous installations' F-N diagram as its landslide risk tolerance criteria.

4.2 Risk Tolerance Criteria: Dams

A number of organizations responsible for dam safety have adopted societal risk tolerance criteria similar to those used for 'potentially hazardous installations' in Hong Kong. These organizations include the International Commission on Large Dams (ICOLD 2003), Australian National Committee on Large Dams (ANCOLD 2003), US Army Corps of Engineers (2008), US Bureau of Reclamation (2012), and Canadian Dam Association (CDA 2012). The corresponding individual risk tolerance criteria adopted by these organizations are all 1:10,000 to 1:100,000.

4.3 Risk Tolerance Criteria: Landslides

4.3.1 Hong Kong

As mentioned in Section 4.1 of this report, the Hong Kong Geotechnical Engineering Office (GEO 1998) proposed that the F-N diagram adopted by the Hong Kong Government for 'potentially hazardous installations' be adopted as societal risk tolerance criteria for 'landslides and boulder falls from natural terrain' (Figure 7 of this report). GEO added the 'Intense Scrutiny' zone for fatalities between 1,000 and 5,000:

"... to provide an option to regulators to permit certain types of developments. Such developments may not necessarily be unacceptable but would be examined with special scrutiny considering the social needs" (GEO 1998)

The criteria were initially adopted as 'interim' in 1998, but are now routinely used in Hong Kong to assess the landslide risk tolerance associated with construction of buildings, roads, and other facilities close to either natural or man-made slopes (Wong 2005).

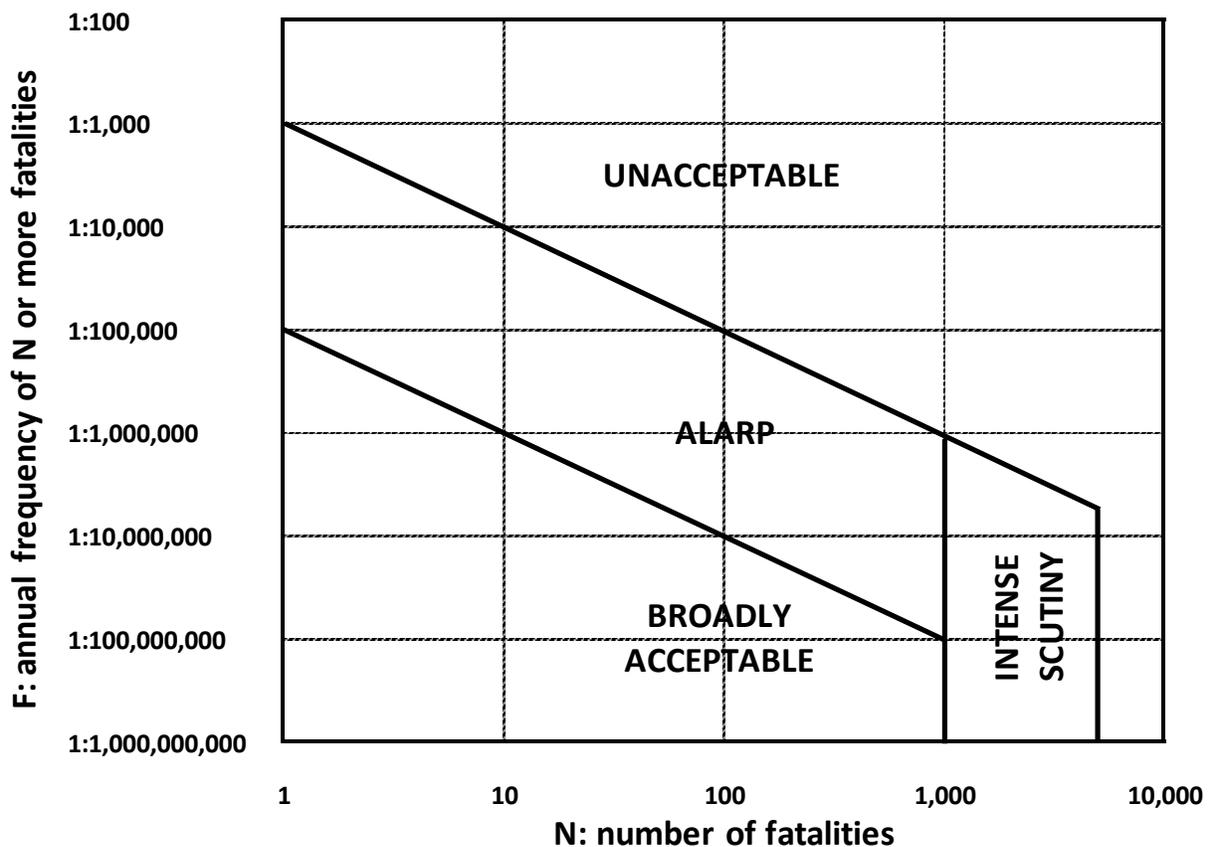


Figure 7. Societal risk tolerance criteria for landslides in Hong Kong (GEO 1998).

Malone (2005) summarizes how the United Kingdom HSE’s formal risk assessment process for ‘potentially hazardous installations’ influenced the formulation of Hong Kong GEO’s landslide risk tolerance criteria. GEO concluded that HSE’s methodology for establishing risk tolerance criteria, with some calibration, could aid decision-making in Hong Kong with respect to both man-made and natural slopes. With respect to natural slopes, GEO does not include in its inventory very infrequent large landslides that are inferred only from the geological record. This policy distinguishes the situation in Hong Kong from that on Cheekye Fan, where both recent landslides and those inferred from the geological record are included in the inventory. Panel #2 recommendations in Section 5.2 of this report provide a method for bridging this gap.

As discussed in Section 4.1, the societal risk tolerance criteria used in Hong Kong are more conservative, by an order of magnitude, than those recommended by the United Kingdom (compare Figures 6 and 7).

In addition to the F-N diagram for societal risk, GEO also prescribes individual risk tolerance criteria of 1:10,000 for existing residential areas and 1:100,000 for new construction. As mentioned in Section 3.5 of this report, societal risk includes risk to both existing and new residential development, and therefore there is only a single F-N diagram for societal risk. In

the context of the F-N diagram for societal risk tolerance criteria (Figure 7), the 1:10,000 individual risk tolerance criterion implies an approximate position in the centre of the ALARP zone for an individual fatality.

The ALARP approach has been applied quantitatively to some cases in Hong Kong to determine the feasibility of landslide remedial works (Wong 2005).

4.3.2 Australasia

Australia

Following the 1997 Australian Thredbo landslide, which, with 18 fatalities, is the deadliest landslide in that country to date, the Australian Geomechanics Society (AGS) developed a framework for risk-based landslide management (AGS 2000). The framework specifies that “risk evaluation is to be done by comparing estimated risks to levels of tolerable or acceptable risk, in order to assess priorities and options”, and the risk tolerance criteria are to be decided by the “client/owner/regulator with advice from a technical specialist”. Although no risk tolerance criteria in Australia are legally binding unless they are accepted by the owner/regulator (AGS 2000, 2007), the Hong Kong landslide tolerance criteria for both individual and societal risks have been supported in publications relating to the Australian landslide risk management practice (Fell et al. 2005).

The Coroner’s report on the Thredbo landslide recommends that the AGS (2000) criteria be considered in revising the Australian Building Code (Hand 2000).

New Zealand

New Zealand’s Resource Management Act delegates risk tolerance criteria to local governments. Following the earthquakes in 2010 and 2011, the City of Christchurch adopted individual risk tolerance criteria similar to those used in Hong Kong. The application of this risk-based policy is currently being tested in New Zealand courts and may eventually be adopted by other jurisdictions within that country. There are presently no land-use development restrictions on debris flow deposits, which might be only hundreds of years old, on the flanks of active volcanoes (M. McSavenney, GNS Science, New Zealand), personal communication, 2015). The New Zealand trend to adopt individual risk tolerance criteria is described by Enright (2015).

4.3.3 Switzerland

In 2005, the Swiss National Platform for Natural Hazards (PLANAT) proposed an individual landslide risk “goal” of 1:100,000 per year (Bruendl et al. 2009). Subsequent decisions by the Swiss Government, however, seem to have rejected the use of risk tolerance criteria for natural hazards. A document published by the Swiss Ministry of the Environment makes the point that, while industrial risks can be controlled by legislation using risk tolerance criteria, natural hazard risks cannot be controlled in the same way (OFEV 2011). The latest PLANAT (2014) publication to discuss tolerable landslide risk criteria states:

“The average risk of death for human beings is not significantly increased by natural hazards. The annual risk of being killed as a result of natural hazards is significantly lower than the average probability of death for the age group with the lowest mortality rate in Switzerland.”

Panel #2 observes that Swiss authorities rely only on landslide hazard probability assessments (as discussed in Section 4.4.1 of this report) and do not consider landslide risk assessments.

4.3.4 Canada

Association of Professional Engineers and Geoscientists of British Columbia (APEGBC)

The APEGBC document “Legislated Landslide Assessments for Proposed Residential Developments in BC” suggests that landslides can be assessed using quantitative risk methods and quantitative risk tolerance criteria (APEGBC 2006, revised 2008 and 2010). The Hong Kong landslide risk tolerance criteria are mentioned as an example. However, APEGBC also suggests that, in some circumstances, qualitative risk and both qualitative and quantitative hazard probability assessments can be used.

District of North Vancouver, BC

Following a 2005 landslide in the District of North Vancouver, the District initiated risk management of natural hazards within its jurisdiction. Based on a BGC report and with input from a task force of community citizens that was convened specifically to explore this issue, the District developed landslide risk tolerance criteria that were adopted by its Council in 2009 (District of North Vancouver 2009).

The District of North Vancouver criteria, presented in Table 1, were established to help evaluate landslide risk to life associated with both existing and proposed residential development. They are compatible with recommended approaches for assessing landslide risk outlined in APEGBC (2006). The District of North Vancouver did not establish or adopt societal risk tolerance criteria for natural hazards.

Table 1: District of North Vancouver individual landslide risk tolerance criteria (adapted from District of North Vancouver 2009).

Application type	Risk <1:10,000)	Risk <1:100,000)
Building Permit (<25% increase to gross floor area)	X	
Building Permit (>25% increase to gross floor area and/or retaining walls >1.2 m)		X
Re-zoning		X
Sub-division		X
New Development		X

Notes:

1. Risk is the annual probability of fatality for the individual most at risk.
2. 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.

These landslide risk tolerance criteria are applied during the development and building permit phases of development. Porter et al. (2007, 2009) provide additional details.

Town of Canmore, Alberta

In June 2013, extreme rainfall caused flooding, debris floods, and debris flows that damaged buildings and other infrastructure on the Cougar Creek fan in Canmore, Alberta.

In response, the Town of Canmore retained BGC to carry out a quantitative risk assessment on the Cougar Creek fan. BGC's assessment involved estimating the hazard probability of debris floods and associated downstream effects on elements at risk. The principal objective of the assessment was to support decisions and expenditures to reduce debris flood risk to a level considered tolerable to both the residents and the politicians. The quantitative risk assessment involved four steps for different debris flood scenarios:

1. assess consequences to buildings and infrastructure,
2. assess vulnerability of critical facilities (e.g., schools, police station) to loss of use,
3. assess risk to life for persons located in buildings, and
4. recommend measures to optimize debris flood reduction measures.

Debris flood scenarios with return periods that ranged from 30-100 years to 1,000-3,000 years, were selected from the field-estimated magnitude-cumulative frequency relationship. The quantitative risk assessment focused primarily on direct building damage, injury, and loss of life using the risk tolerance criteria developed in Hong Kong (Section 4.3.1 of this report) (Town of Canmore 2015).

A total of 190 lots in Canmore were identified where the average risk to life of an individual from a debris flood was estimated to exceed 1:10,000 per year and was considered unacceptable (BGC 2014). Estimated societal risk was also estimated to be unacceptable. Moving that part of the community potentially at risk was considered impractical, thus Canmore assessed mitigation options, leading to the decision to construct a debris flood containment structure to reduce the individual risk and the societal risk to within the ALARP zone. The decision required consideration of issues of 'feasibility, fairness, and affordability'. A containment structure approximately 30 m high and 110 m long, with a storage capacity of 625,000 m³, is currently being designed.

Canmore's use of a quantitative risk assessment approach was essential to gain stakeholder support. In so doing, Canmore was praised and benefited from partial financing from the Province of Alberta.

4.4 Landslide Hazard Probability Tolerance

As mentioned previously, jurisdictions in many countries still base their landslide management strategies on hazard probability characterized by the intensity of landslide impact and the associated probability of encounter. This is referred to as 'landslide hazard probability assessment', as opposed to 'landslide risk assessment'.

4.4.1 Switzerland

The Swiss Government uses a hazard probability mapping convention for land-use planning assessments (OFAT 1997) (Figure 8).

The suggested planning actions associated with the hazard probability zones, adapted from Lateltin et al. (2005), are as follows:

- High Hazard: in principle, no construction used to shelter people or animals is allowed; if buildings exist, they cannot be enlarged or reconstructed.
- Moderate Hazard: buildings are allowed only under certain conditions; hospitals or major development projects ('sensitive objects') should not be allowed.
- Low Hazard: building is allowed, but landowners should be informed of the existing hazard; special protection measures are taken for 'sensitive objects'.
- Very Low Hazard: standard buildings are allowed without special requirement, but special protection measures must be taken for 'sensitive objects'.

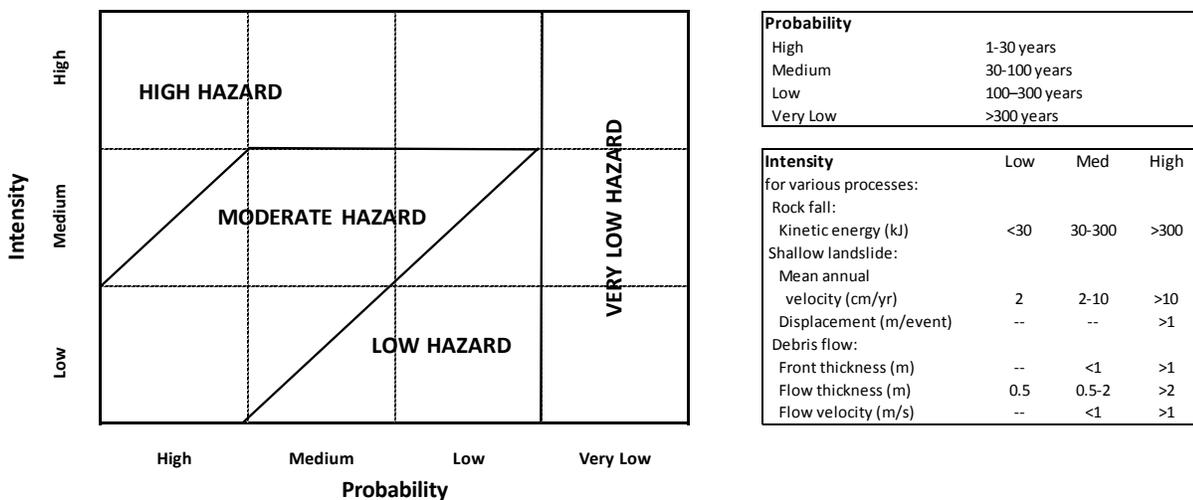


Figure 8: Swiss matrix for hazard probability mapping (adapted from OFAT 1997, Lateltin et al. 2005).

Swiss hazard probability tolerance zones have limited legality unless they are approved by the local council and incorporated into local land-use management plans.

Any change to a local land-use management plan must also be vetted by cantons (local Swiss jurisdictions). To ensure consistency in landslide management, many cantons have appointed special natural hazards commissions comprising political authorities, administrative officers, scientists, and public insurers. The commissions can propose new policies with respect to hazardous zones, as happened after the Chlowena landslide in 1994, when all the building in High Hazard zones was suspended (Vulliet and Bonnard 1996).

These policies are accepted and applied in most Swiss cantons, but with some modifications because land-use planning has to be adapted to the political traditions of the individual canton to gain acceptance (Lateltin et al. 2005).

4.4.2 United States

A uniform approach to landslide management does not exist in the United States. There are very few detailed landslide hazard probability maps in the United States, and land-use

decisions are typically made by counties and cities. Where such maps exist, they typically focus on recognized unstable areas and do not provide information on future landslide hazards or risks.

Orting, Washington

An interesting case study in the United States is the development regulations in Pierce County, Washington, where some communities, such as Orting (Figure 9), are located on a 500-600-year-old *lahar* (the Electron Mudflow) that originated from Mt. Rainier, 50 km away (Pierson et al. 2014). Four hazard probability zones, with 100-year to 1,000-year return periods, have been recognized by the US Geological Survey (Pierce County 2014). Building restrictions in these zones are applied to high occupancy buildings and sensitive infrastructure, and depend on a warning system. There are, however, no restrictions on the construction of other buildings, including single family dwellings. The US Geological Survey maintains an active lahar monitoring system on Mt. Rainier, and detailed evacuation plans are in place.



Figure 9: Town of Orting, Washington, 50 km distant from Mt. Rainier (Pierson et al. 2014).

There are no engineered mitigation structures in the valleys surrounding Mt. Rainier. It appears that the acceptance of individual and societal risks at Orting and other communities in the region is based on the assumption that the warning system will provide sufficient time for evacuation. This time may be several days in the case of eruption of Mt. Rainier, but only 0.5 to 1.5 hours for non-eruptive landslides and debris flows, provided that the warning

system is effective. Property owners are informed of the existence of landslide and volcanic hazards through clauses attached to their land titles, and there are periodic evacuation exercises (Pierson et al. 2014). In comparison, if a warning system was installed on Mt. Garibaldi, the warning time for Cheekye Fan would be, at most, several minutes.

4.4.3 Norway

In Norway, there are concerns that damaging tsunamis could result from rock slides or rock falls into fjords or lakes. Several tens of fatalities resulted from such events in the 20th Century (Blikra et al. 2005). At present, several slowly moving steep unstable slopes above Norwegian fjords are being continuously monitored and at-risk communities have evacuation plans if movement accelerates above a defined threshold.

Guidelines established by the Direktoratet for Byggequalität (2015) specify development restrictions in areas subject to landslides or landslide-generated waves. These restrictions include single and multi-family structures with less than 10 households, which can only be built where the probability of landslide impact is less than the 1,000-year return period event. Larger buildings and facilities designed for concentrated use, such as schools, must be located in areas where the probability of landslide impact is less than the 5,000-year return period event. The regulations provide for exceptions in cases where “the consequences of building restrictions are serious and the construction has significant impact on the society.” Other exceptions are provided in cases where a warning can be issued 72 hours before the event.

4.4.4 Canada

Rubble Creek, BC

The Rubble Creek fan, located 20 km north of Cheekye Fan, was the site of a large rock slide-debris flow in the mid-1800s. In 1973 Mr. Justice Thomas Berger of the Supreme Court of BC made a precedent-setting decision to uphold a BC Ministry of Transportation and Infrastructure (BC MOTI) Approving Officer’s decision not to approve a proposed 126-lot community. He ruled that there was sufficient probability of a catastrophic landslide occurring during the life of the community, and negatively affecting it, to disallow its development (Berger 1973). Justice Berger noted that communities typically have life expectancies of at least several hundreds of years. This ruling has been interpreted as corresponding to a tolerable hazard probability of the 10,000-year return period event, although Justice Berger did not specify this probability (VanDine and Lister 2011).

Justice Berger’s decision should be viewed in the context in which it was made:

- there was no discussion of mitigation of the hazard;
- the potential consequence of a landslide comparable to that in the mid-1800s was certain, resulting in the death of everyone in the proposed community;
- the proposed community was new and was being located in an area where there was no existing development; and
- there were alternative locations for the new community, one of which was eventually used.

Fraser Valley Regional District, BC

In the early 1990s, the Fraser Valley Regional District published hazard probability tolerance criteria for a variety of natural hazards and a range of residential development (Cave 1992, revised 1993). These criteria, which are still used by the District today, were based on the 200-year return period event for floods, the BC MOTI's guideline of the ~500-year return period event (10% annual probability of at least one event occurring in 50 years) (BC MOTI 1993), and a 10,000-year return period event as interpreted from Justice Berger's decision (Berger 1973). These criteria imply that these events could potentially damage, or cause fatalities in, residential developments. In other words, potential consequences are implicit within the hazard probabilities.

District of Squamish, BC

Based on the hazard zones defined by TEL-GAL (1993) (Figure 3), the District of Squamish regulates land use on Cheekye Fan by means of its Official Community Plan (OCP) that is based on the 1:10,000-year return period debris flow event (District of Squamish 2009). The resulting OCP policy includes a requirement to avoid development in zones 1 and 2 (higher hazard zones) and to require a 'Debris Flow Mitigation Plan' and appropriate mitigation measures in zones 3 and 4 (lower hazard zones) (see Section 2.3).

BC Ministry of Transportation and Infrastructure

In 2009, the BC MOTI, in an internal document entitled "Subdivision Preliminary Layout Review - Natural Hazard Risk" (BC MOTI 2009, revised 2013 and 2015), provided guidance with respect to hazard probability tolerance criteria. The document superseded BC MOTI (1993) and accompanies its website "Rural Subdivision Approvals – 2.3.1.07 Geotechnical Study"¹¹. Paraphrased from that document, landslide hazard probability tolerance criteria , , are:

- for a building site, unless otherwise specified, ~500-year return 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 event; and
- large-scale developments must also consider total risk and refer to international standards.

BC MOTI's criteria of the ~500-year return period event was based on the pre-2005 National Building Code of Canada (for example, NBCC 1995), which referred to earthquake probability for ground motions for seismic building design to minimize loss of life (VanDine and Lister 2011). The 10,000-year return period event apparently was based on the 1973 Justice Berger decision.

Association of Professional Engineers and Geoscientists of British Columbia

In 2012, APEGBC published "Professional Practice Guidelines – Legislated Flood Assessments in a Changing Climate in BC" (APEGBC 2012). Although the focus of these guidelines is flooding, they also address several non-conventional flood-related hazards,

¹¹ (http://www.th.gov.bc.ca/DA/manual1/manpage.asp?page=2.3.1.07_Geotechnical_Study.asp)

including debris flows and debris floods. Appendix E of that document provides guidance for hazard mapping. With several caveats, the document suggests a 2,500-year return period event be considered as the limiting hazard probability for debris flows, debris floods, and landslide-dam breach hazards for large and very large subdivisions (more than 100 single family lots, and for new subdivisions and communities). Examples of past events that have similar hazard probabilities are lahars that could impact Pemberton, BC, and landslide dam-outbreak floods that could impact the upper Squamish River. The document notes that debris flow volumes and peak discharges for an event exceeding the 1,000-year return period are exceedingly uncertain and in many cases are at the limits of available geological dating methods.

Appendix J of those guidelines, however, also suggests:

“For life-threatening events including debris flows, the Ministry of Transportation and Public [sic] Infrastructure stipulates in their 2009 publication ‘Subdivision Preliminary Layout Review – Natural Hazard Risk’ that a 10,000-year return period [event] needs to be considered”.

Section 5: Advice on Landslides Risk Tolerance Criteria

This section addresses the first and fourth tasks asked of Panel #2: landslide risk tolerance criteria for Cheekye Fan and whether these criteria can be applied over the entire District of Squamish.

Paraphrasing from the introduction to APEGBC (2006, revised 2008 and 2010):

It is **not** the role of a Professional Engineer or Professional Geoscientist to define [landslide risk tolerance criteria]; [such criteria] must be established and adopted by the local government or the provincial government after considering a range of societal values. [emphasis in the original]

Therefore, as mentioned previously in this report, Panel #2 can provide valuable input for determining landslide risk tolerance criteria, but stakeholders and jurisdictional decision-makers ultimately have to select, by means of an appropriate public process, the risk evaluation parameters (hazard probability, and landslide volume and/or peak discharge) for a particular situation or jurisdiction. Decisions on land use and engineered structural mitigation, or some combination of the two, must balance competing interests and societal values, while at the same time protecting public safety.

5.1 Landslide Risk Tolerance Criteria

Panel #2 Task 1: Advise on landslide risk tolerance criteria for existing and proposed new development on Cheekye Fan.

Regardless of the landslide risk tolerance criteria being considered, it is Panel #2's opinion that the following landslide risk assessment principles should apply:

- Landslide risk tolerance criteria should be established within the framework of the landslide risk management process shown on Figure 4 in Section 3.1 of this report.
- Landslide risk assessment should rely on quantitative risk analysis. An example of an acceptable method for conducting quantitative risk analysis is that used by BGC for Cheekye Fan (BGC 2008a, 2008b), which is similar to those used for the District of North Vancouver, BC (Porter et al. 2007, 2009) and the Town of Canmore, Alberta (BGC 2014). Panel #2 recognizes that there are uncertainties associated with this method but is of the opinion that such uncertainties are best addressed if and when conceptual designs advance to more detailed designs.
- The landslide magnitude-cumulative frequency (total volume-return period) relationship for Cheekye Fan should be based on that prepared by BGC (2008a) and presented in the Panel #1 report (Clague et al. 2014; Figure 3 of that report, reproduced as Figure 10 of this report). As discussed in the Panel #1 report, the upper, dotted line on the right side of Figure 10 is recommended for large landslides.

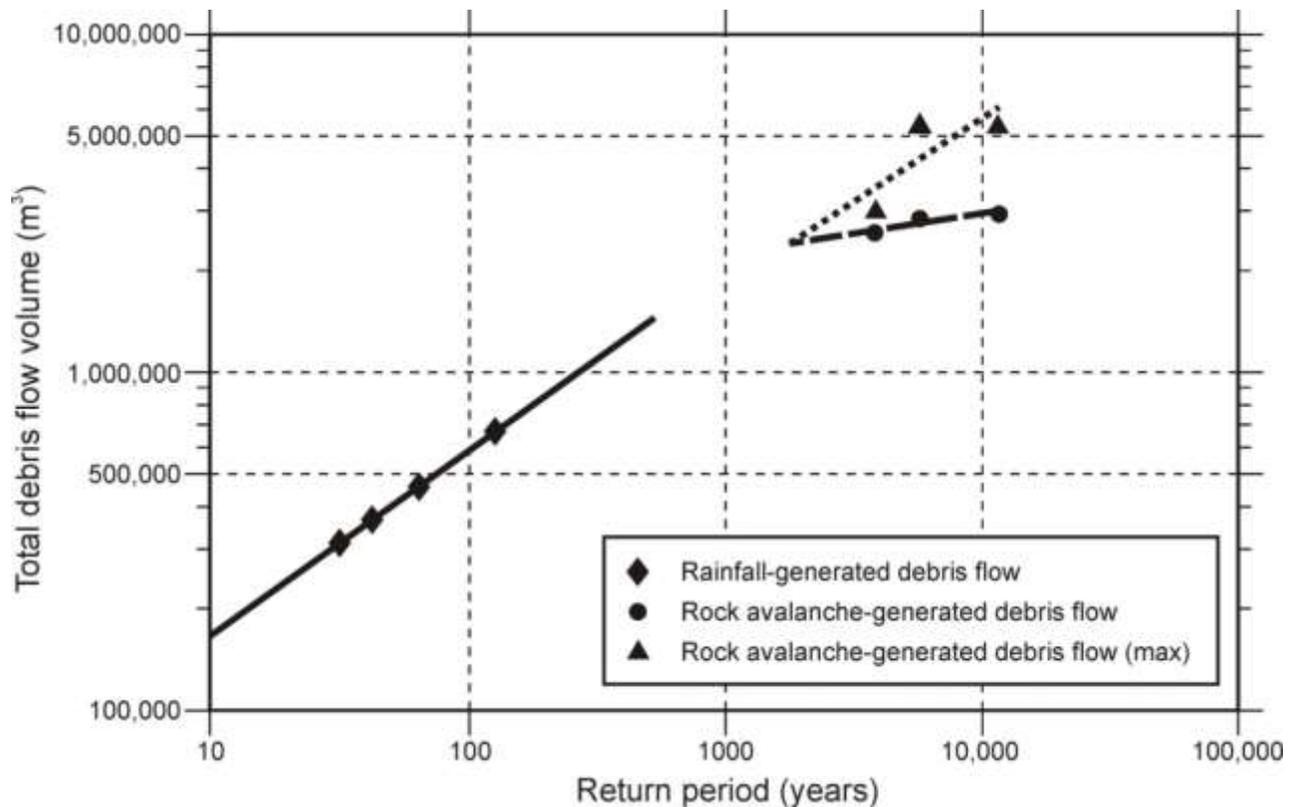


Figure 10: Magnitude-cumulative frequency relationship for Cheekye Fan (from BGC 2008a). Refer to the Panel #1 report (Clague et al. 2014) for details.

Based on the above principles, Panel #2 recommends that the Hong Kong landslide risk tolerance criteria be adopted for Cheekye Fan. The recommended risk-to-life criteria are summarized as:

1. Individual annual risk tolerance criteria should be less than 1:10,000 for existing development and less than 1:100,000 for new construction.
2. Societal annual risk tolerance should be based on the Hong Kong Geotechnical Engineering Office F-N diagram (Figure 7 of this report, replicated as Figure 11).

For comparison, Section 3.3 of this report provides examples of an individual's annual risk of dying from some everyday activities or causes.

It is Panel #2's opinion that estimated societal risks, for both existing and new development, should fall within the ALARP ('as low as reasonably practicable') zone. 'Reasonably practicable' can be determined qualitatively by qualified professionals based on costs and i) land-use decisions and/or land-use restrictions; ii) analyses of the location, layout, and design of engineered structural mitigation; or iii) a combination of both.

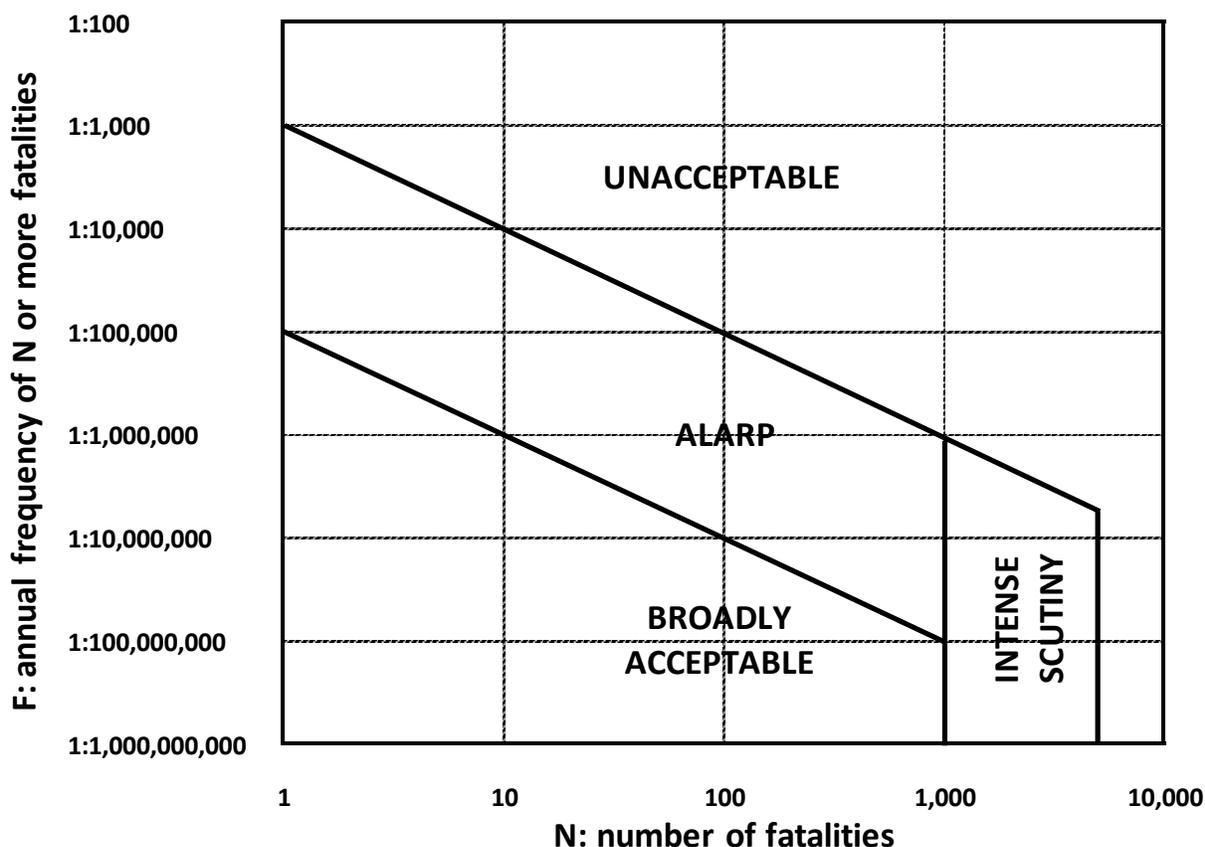


Figure 11: Recommended F-N diagram for societal landslide risk tolerance criteria for Cheekye Fan (identical to that for Hong Kong; Figure 7, Section 4.3.1).

As discussed in Section 4.3.1 of this report, Hong Kong included an ‘Intense Scrutiny’ zone in its F-N diagram for societal landslide risk tolerance criteria. The intent of this zone is:

“to provide an option to regulators to permit certain types of developments. Such developments may not necessarily be unacceptable but would be examined with special scrutiny considering the social needs” (GEO 1998).

Because of the relatively low population density in most of rural BC, compared to that of Hong Kong, it is Panel #2’s opinion that the ‘Intense Scrutiny’ zone would seldom be a factor in most landslide risk assessments in rural BC. If it were, however, any associated development would have to be investigated with considerably more than the standard level of effort, as in Hong Kong.

Consistent with Hong Kong practice, Panel #2 recommends that the above risk-to-life criteria be considered only as guidelines and used as one input into the decision-making process.

Risk tolerance criteria cannot be established for elements at risk, other than risk to life. Other elements at risk, such as property, the environment, and financial interests, are typically

evaluated by comparing costs of potential losses against costs of preventing those losses (cost-benefit analyses).

5.2 Landslide Risk Evaluation Process

The landslide risk evaluation process is a complex undertaking, especially with respect to landslides on Cheekye Fan. Technical input, such as this report, informs the process, but ultimately the stakeholders and decision-makers must select appropriate risk evaluation parameters (hazard probability, and landslide volume and/or peak discharge). As described below, the experiences of the District of North Vancouver and Canmore, Alberta, should be considered in this regard.

To help develop its landslide management strategy, the District of North Vancouver, convened a task force to help establish its risk tolerance criteria for natural hazards. As described in Tappenden (2012), the task force consisted of eight volunteer citizens with a variety of backgrounds that were selected to represent the community. The task force participated in educational sessions on relevant topics and was provided with, and reviewed, relevant literature from other jurisdictions. The task force also solicited input from the larger community by means of an open house, a public meeting, and an online survey. After deliberation, the task force presented its recommendations for risk tolerance criteria to the District. Although the purpose of this process was to establish risk tolerance criteria, a similar process could be used to establish appropriate risk evaluation parameters.

In 2014, prior to selecting options to mitigate debris flows and debris floods, the Town of Canmore found it valuable to engage focus groups of both affected and non-affected residents to help it determine preferences and sensitivities that could have a bearing on decisions and the way in which information was presented. Canmore also adopted a structured decision-making process at a critical stage in its risk evaluation. A similar process could be used by the District of Squamish to establish appropriate risk evaluation parameters.

A variety of competing societal values must be considered in the landslide risk evaluation process. These include, but are not limited to, desires to:

- achieve public safety, a moral issue (for example, APEGBC's Code of Ethics #1 states that a professional engineer or professional geoscientist must hold paramount the safety, health, and welfare of the public and the protection of the environment);
- mitigate existing risks in an economically feasible manner;
- increase availability of suitable and affordable residential land in the District of Squamish;
- maximize value to the community from a currently 'sterilized' land asset;
- maximize return on investment;
- minimize long-term obligations of decision-makers, developers, and land managers; and
- preserve traditional, cultural, and recreational land values.

In the landslide risk evaluation process, stakeholders and decision-makers should consider all elements at risk, including those with associated economic losses. Potential economic losses

should be quantified and cost-benefit analysis can be used to guide decision-making.

5.3 Landslide Risk Evaluation Parameters

Stakeholders and jurisdictional decision-makers must consider societal values when selecting the risk evaluation parameters (hazard probability and landslide volume and/or peak discharge) that are appropriate to the location and situation. Specifically, selection of the upper limit of the return period (as in Figure 10 of this report) will determine the upper limit of the landslide volume and/or peak discharge to be considered in the quantitative risk assessment. However, the greater the return period (the less probable the hazard), the more uncertainty there is in the corresponding estimates of landslide volume and/or peak discharge.

In making this choice, there is always an acceptance of some residual risk from not considering larger landslides. By analogy, if structures are designed for a 2,500-year return period earthquake, as prescribed by the National Building Code of Canada, there is risk of damage if a larger (less probable, for example a 5,000-year return period) earthquake occurs. Therefore, when an event with a particular return period is selected, if the residual risk is relatively low, the uncertainty in the estimates of landslide volume and/or peak discharge will be relatively high, and vice versa.

The challenge to stakeholders and jurisdictional decision-makers is to balance the residual risk with the perceived benefits of development. For Cheekye Fan, Panel #2 recommends that three suites of landslide hazard probability options (Options 1, 2, and 3) be considered. The hazard probabilities refer to the return periods shown on the magnitude-cumulative frequency curve produced by BGC (2008a) and reproduced as Figure 10 of this report. Options 1, 2 and 3 are highlighted on Figure 12.

Option 1

The quantitative risk assessment is based on a suite of landslide hazard probabilities up to and including the 10,000-year return period event (bold dashed line on Figure 12).

This option has a precedent in Justice Berger's 1973 decision for Rubble Creek, and this decision appears to have been adopted as the basis of a hazard probability tolerance criteria by the Fraser Valley Regional District (Cave 1992, revised 1993), the District of Squamish for its OCP hazard zones for Cheekye Fan (District of Squamish 2009), and the BC MOTI (2009, revised 2013 and 2015) (Section 4.4.4). With respect to Justice Berger's decision, the Rubble Creek situation was, however, quite different from that on Cheekye Fan for a number of reasons described in Section 4.4.4 of this report.

Based on its collective experience and a survey of the literature, Panel #2 knows of very few examples where the 10,000-year return period landslide has been used for a quantitative risk assessment, and most of these studies were done by BGC in the Province of BC. Some of these studies involved revisions to the estimated volume or peak discharge of the 1:10,000-year return period event due to uncertainties associated with its definition. In one case, it was recommended that the risk associated with the lowest-probability events could be tolerated as

residual risk. Towards the other end of the spectrum, Hong Kong, for example, bases its hazard probability scenarios on information provided by detailed landslide inventories prepared from airphotos and therefore based only on relatively recent landslides (Malone 2005).

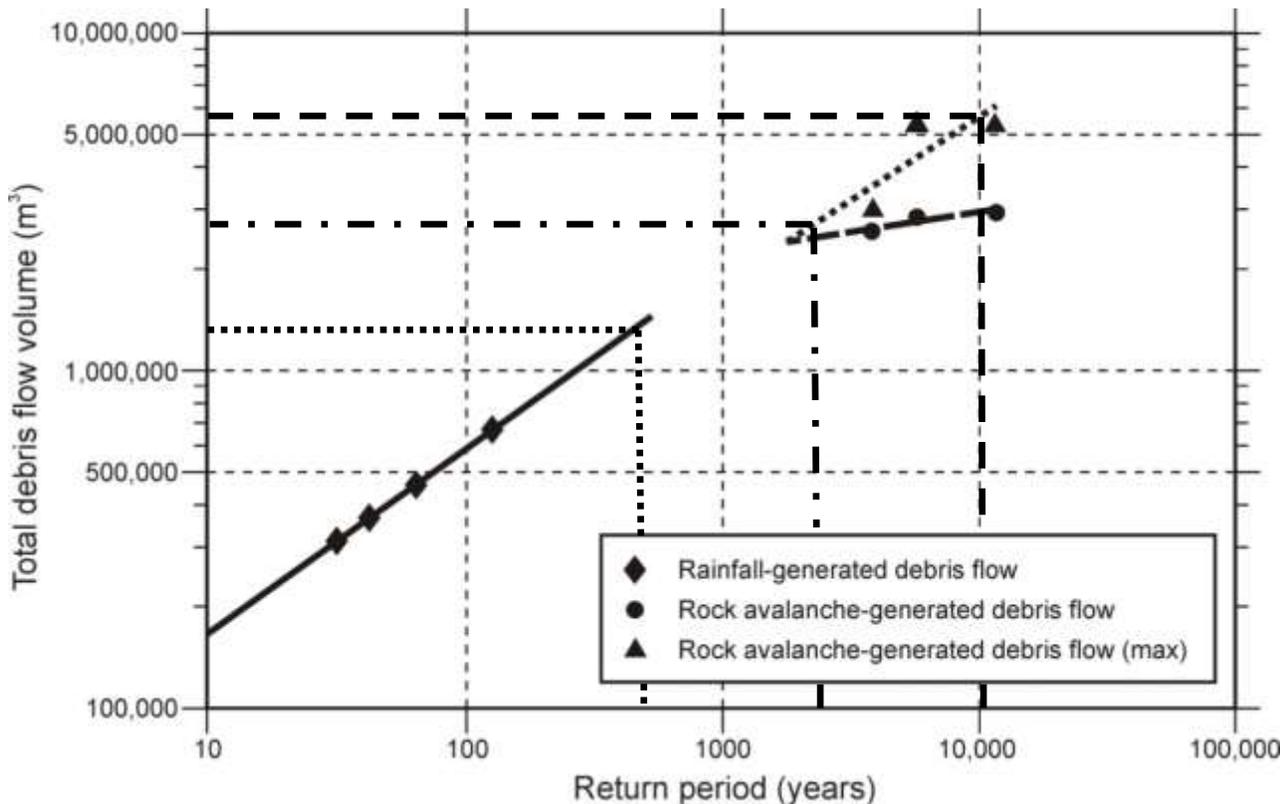


Figure 12: Magnitude-cumulative frequency relationship for Cheekye Fan (from BGC 2008a) showing landslide hazard probability options: 10,000-year, 2,500-year, and 500-year return period events and associated total debris flow volumes depicted, respectively, as bold dashed, dashed-dotted, and dotted lines.

Similarly, Panel #2 knows of very few precedents of engineered mitigation structures for landslides that have been designed based on a 10,000-year return period landslide, and knows of none that have been constructed. Panel #2 is aware, however, that the 10,000-year return period stream flood event, has been used for dam and reservoir design and construction in the United States and for sea dike design and construction in the Netherlands.

Option 2

The quantitative risk assessment is based on a suite of landslides hazard probabilities up to and including the 2,500-year return period event (bold dashed-dotted line on Figure 12).

This option is consistent with the APEGBC flood assessment guidelines (APEGBC 2012) for debris flows and debris floods for large and very large subdivisions (greater than 100 single-family lots, and for new subdivisions and communities) (Section 4.4.4).

This option is also consistent with the current National Building Code of Canada’s earthquake hazard probability for ground motions for seismic building design (NBCC 2005). That document, which only addresses the structural safety of buildings to minimize loss of life, considers earthquakes with a hazard probability up to the ~2,500-year return period event. As such, it reflects a societal view on an appropriate standard of care. From that document:

“The primary objective of seismic design is to provide an acceptable level of safety for building occupants and the general public as the building responds to strong ground motion; in other words, to minimize loss of life. This implies that, although there will likely be extensive structural and non-structural damage, during the DGM (design ground motion [from an earthquake with a return period greater than 2,500-years]), there is a reasonable degree of confidence that the building will not collapse nor will its attachments break off and fall on people near the building. This performance level is termed ‘extensive damage’ because, although the structure may be heavily damaged and may have lost a substantial amount of its initial strength and stiffness, it retains some margin of resistance against collapse” (NBCC 2005).

Panel #2 recognizes that seismic hazards are not the same as landslide hazards, but there are similar processes involved in balancing societal values. For example, residual risk must be a consideration for both landslides and earthquakes.

Option 3

The quantitative risk assessment is based on a suite of landslide hazard probabilities up to and including the 500-year return period event (bold dotted line on Figure 12).

This option is consistent with BC MOTI’s (1993 and 2009, revised 2013 and 2015) guidance for a damaging event to a building site. This guidance was based on the earthquake hazard probability for ground motions for seismic building design to minimize loss of life, as adopted by the National Building Code of Canada prior to 2005 (Section 4.4.4).

Summary

The above three options are summarized in Table 2.

Table 2: Recommended suites of landslide hazard probability options that should be considered.

Option	Based on a suite of landslide hazard probabilities <u>up to and including</u>	Rationale*
1	10,000-year return period event	Rubble Creek (Berger 1973) Regional District of Fraser Valley (Cave 1992 revised 1993) District of Squamish (2009) BC MOTI (2009 revised 2013)
2	2,500-year return period event	APEGBC (2012) (for debris flows and debris floods) NBCC (2005) (for earthquakes)
3	500-year return period event	BC MOTI (1993, 2009 revised 2013)

General Comments

Panel #2 notes that only a few jurisdictions consider very infrequent events in land-use management decisions based on hazard probability criteria, as opposed to risk criteria. The District of Squamish's OCP for Cheekye Fan, however, is one example where a jurisdiction does consider very infrequent landslides (see Section 4.4.4). Panel #2 also notes that development restrictions in Switzerland, Austria, Italy, and France only exist for locations where there is clear evidence of current instability.

In addition to being informed by quantitative risk assessments based on the above three options, stakeholders and jurisdictional decision-makers should consider, for comparison, the 'base case' of no mitigation. In the case of Cheekye Fan, this is the existing situation of designing for the 200-year return period stream flood. This consideration will help put the landslide hazard probability decision in context.

The three return period event options (10,000-year, 2,500-year, and 500-year) described above and summarized in Table 2 and shown on Figure 12 involve progressively more certainty in estimates of landslide volume and/or peak discharge and less mitigation efforts, but increasing residual risk that would have to be tolerated by the community.

In addition to the above three options, and especially if the landslide risk tolerance criteria presented above were to be applied elsewhere in the District of Squamish or indeed elsewhere in the province, other suites of landslides hazard probabilities might be considered.

As mentioned previously, Panel #2's focus was on risk to life. Other elements at risk, such as those listed in Section 3.2 of this report, however, are not to be excluded. In the landslide risk evaluation process, stakeholders and jurisdictional decision-makers should consider all elements at risk including those with associated economic losses.

5.4 Cheekye Fan and the District of Squamish

Panel #2 Task 4: Advise on whether individual and societal landslide risk tolerance criteria can be applied across the District of Squamish or solely to Cheekye Fan.

It is Panel #2's opinion that the landslide risk tolerance criteria presented in Section 5.1 can be applied across the District of Squamish. However, the magnitude-cumulative frequency relationship shown in Figures 10 and 12 is specific to Cheekye Fan; that relationship cannot be used elsewhere. If such a relationship is not available for other locations in the District of Squamish, one would have to be created by qualified professionals.

As mentioned above, there could be justification for considering other suites of landslides hazard probabilities, other than the 10,000-year, 2,500-year, and 500-year return period events described above and shown in Figure 12, for other locations in the District of Squamish.

Section 6: Advice on Landslide Risk on Cheekye Fan

This section addresses the second and third tasks asked of Panel #2: the existing individual and societal risk from landslides on Cheekye Fan and how risk reduction to existing and proposed new development might be achieved by mitigation.

6.1 Current Levels of Risk

Panel #2 Task 2: Advise on current levels of individual and societal risk from landslides on Cheekye Fan.

BGC provided four draft debris flow model simulation maps to Panel #2. The four maps were prepared at a scale of 1:25,000 with the parameters shown in Table 3.

Table 3: Parameters used for debris flow model simulation maps.

Map	Debris flow depths and velocities for return period (years)	Estimated volume (m ³)	Estimated peak discharge (m ³ /s)
1	10,000	5,500,000	33,000
2	10,000	5,500,000	18,000
3	2,500	2,400,000	12,400
4	2,500	2,400,000	7,000

Although there was no accompanying text, it is Panel #2's understanding that the maps were prepared using a two-dimensional debris flow runout model (FLO-2D), similar to that used to prepare debris flow simulation maps in BGC (2007). No proposed engineered structural mitigation was included in these model simulations. Panel #2 refers to this situation in Section 5.3 (General Comments) of this report as the 'base case'.

In general, all four maps indicate that approximately two-thirds of Cheekye Fan, and specifically the southern two-thirds of the fan, could be impacted by the simulated debris flows. In all cases the simulated debris flow depths and debris flow velocities would be sufficient to cause considerable damage to buildings and infrastructure on the impacted portions of the fan and could result in loss of life. Panel #2 is not in a position to conclude anything else from these maps.

Panel #2 reiterates the following from the Panel #1 report (Clague et al. 2014):

"Existing residential development on Cheekye Fan and on the west side of the Cheekye/Cheekye river confluence, as well as other existing development on the fan, are at risk from both debris flows and debris floods, and from stream floods and associated sediment movement that may or may not be associated with debris flows or debris floods. This development includes:

- a portion of the community of Brackendale, a number of rural residences, and the inhabited First Nation reserves;
- the BC Hydro Cheekye substation and associated transmission lines;

- the Squamish airport;
- some light industry; and
- BC Highway 99, a number of main and subdivision roads, and the CN Rail line.

Any risk assessment must consider the full spectrum of flooding and landslide phenomena, ranging from large volume (with relatively low probability of occurrence) to low volume (with relatively high probability of occurrence).

It is the Panel's opinion that the risks [described in the Panel #1 report] to existing development should be mitigated whether or not there is any future development on Cheekye Fan."

6.2 Risk Reduction by Mitigation

Panel #2 Task 3: Advise on individual and societal risk reduction that might be achieved through mitigation, given existing and proposed new development.

To assist in providing this advice, Panel #2 was provided with:

- BGC Project Memorandum for 'Cheekeye [sic] Fan Debris Flow Mitigation Stage 1 – Concept Development and Validation', prepared for Bethel Lands Corp, October 24, 2014; and
- two simulated oblique views of the preliminary conceptual design of the 'main barrier'; one looking upstream and one looking downstream; prepared by BGC, November 2014.

The design concept is for two engineered structures: a 'main barrier' located on Upper Cheekye Fan immediately south of Cat Lake, and a 'sedimentation basin' located just south of Cheekye River and directly upstream (east) of Highway 99 (see Figure 2 of this report).

Based on BGC's modelling of a 5,500,000 m³ debris flow (the estimated 10,000-year return period event), the main barrier was not overtopped. There was no discussion of how much debris passed through the barrier and continued downstream.

BGC concluded that:

"Based on these analyses, BGC expects that it is technically possible to design and build mitigation structures that can reduce Cheekeye [sic] River debris flow risk to a level that approving authorities could deem to be tolerable."

Because BGC's modelling considered a 5,500,000 m³ debris flow as the design event (the estimated 10,000-year return period event), it is Panel #2's opinion that individual and societal risk reduction to existing and proposed new development could be achieved with some form of engineered structural mitigation, singly or in combination. For Panel #2 to be more definitive in its conclusion, the technical feasibility of such structural mitigation, including an examination of detailed designs and operation and maintenance, would have to be examined.

Stakeholders and jurisdictional decision-makers should take into account existing and proposed mitigation, singly or in combination, when considering the options of suites of landslide hazard probabilities discussed in Section 5.3 of this report.

Panel #2 reiterates the following from the Panel #1 report (Clague et al. 2014):

“Future protection must mitigate debris flows, debris floods, stream floods, and sediment movement. Such mitigation can be accomplished in many ways, ranging from education to zoning to engineered structures, such as retention basins, stream channeling and diking, bridge improvements, or a combination of any of these options. Existing engineered protective structures include berms adjacent to the Don Ross Secondary School in Brackendale and the BC Hydro Cheekye Substation, and along portions of the lower Cheekye River.

It is the Panel’s opinion that, in terms of protecting existing development and possibly allowing some new development on Cheekye Fan, and on the west side of the Cheakamus River across from Cheekye Fan, all forms of mitigation, singly or in combination, should be considered and carefully evaluated.”

To clarify Panel #1’s statement, the phrase “all forms of mitigation” could include engineered mitigation structures, such as debris barriers, deflection berms, and terminal berms, as well as non-structural measures, such as land-use zoning, signage, and education.

References

- AGS (Australian Geomechanics Society). 2000. Landslide risk management concepts and guidelines. *Australian Geomechanics*, v. 35, no. 1, March 2000, reprinted in v. 37, no. 2, May 2002.
- AGS (Australian Geomechanics Society). 2007. A national landslide risk management framework for Australia. *Australian Geomechanics*, v. 42, pp. 1-36.
- AICE (American Institute of Chemical Engineers). 1989. *Guidelines for Chemical Process Quantitative Risk Analysis*. Center for Chemical Process Safety, New York, 585 pp.
- Ale, B.J.M. 2005. Tolerable or acceptable: A comparison of risk regulation in the United Kingdom and in the Netherlands. *Risk Analysis*, v. 25, pp. 231-241.
- ANCOLD. 2003. *Guidelines on Risk Assessment*. Australian National Committee on Large Dams. Sydney, Australia.
- APEGBC. 2006, revised 2008 and 2010. *Guidelines for Legislated Landslide Assessments for Proposed Residential Developments in BC*. Association of Professional Engineers and Geoscientists of the Province of British Columbia, Burnaby, BC, 75 pp.
- APEGBC. 2012. *Professional Practice Guidelines – Legislated Flood Assessments in a Changing Climate of BC*. Association of Professional Engineers and Geoscientists of the Province of British Columbia, Burnaby, BC, 139 pp.
- Baumann, F.W. 1991. *Report on the Garbage Dump Debris Flow Deposit and Its Relationship to the Geologic History of the Cheekye Fan*. Baumann Engineering, Squamish, BC, 25 pp.
- BC MOTI (Ministry of Transportation and Infrastructure). 1993. *Subdivision Policy and Procedures Manual*, Systems Planning Research Officer, Victoria, BC.
- BC MOTI (Ministry of Transportation and Infrastructure). 2009, revised 2013 and 2015. *Subdivision Preliminary Layout Review – Natural Hazard Risk*, internal document, March 13, 2009
- Berger, T.B. 1973. *Reasons for Judgment for the Honourable Mr. Justice Berger on the Matter of the Land Registry Act – And on Application for Approval of a Proposed Subdivision by Cleveland Holdings Ltd*. Supreme Court of British Columbia, Victoria, BC, 26 pp.
- BGC (BGC Engineering Inc.). 2007. *Cheekye River Debris Flow Simulations*. Final report to Kerr Wood Leidal Associates, December 2007.
- BGC (BGC Engineering Inc.). 2008a. *Cheekye River Debris Flow Frequency and Magnitude*. Final report to Kerr Wood Leidal Associates, January 2008.
- BGC (BGC Engineering Inc.). 2008b. *Cheekye River Debris Flow Risk Assessment*. Final report to Kerr Wood Leidal Associates, October 2008.
- BGC (BGC Engineering Inc.) 2014. *Cougar Creek Debris Flood Risk Assessment Report*, for the Town of Canmore
- Blikra, L.H., Longva, O., Harbitz, C. and Løvholt, F. 2005. Quantification of rock-avalanche and tsunami hazard in Storfjorden, western Norway. *In Landslides and Avalanches*, ed. Senneset, K., Flaate, K. and Larsen. J.O. Taylor & Francis Group, London, pp. 57-64.
- Bruendl, M., Romang, H.E., Bischof, N. and Rheinberger, C.M. 2009. The risk concept and its application in natural hazard risk management in Switzerland. *Natural Hazards and Earth Systems Science*, v. 9, pp. 801–813.

- Cave, P.W. 1992 (revised 1993). Hazard acceptability thresholds for development approvals by local government. In Proceedings of the Geological Hazards Workshop, Victoria, BC, ed. Bobrowsky, P. BC Geological Survey Branch, Open File 1992-15, pp. 15-26.
- CDA (Canadian Dam Association). 2013. Dam Safety Guidelines. Canadian Dam Association, Edmonton, AB.
- Cheekye Fan Geotechnical Review Board. 2007. Letter to Mr. Bordian of MacDonald Development, dated May 31, 2007.
- Cheekye Fan Geotechnical Review Board. 2008a. Letter to Mr. Gerry Bordian of MacDonald Development, dated March 4, 2008.
- Cheekye Fan Geotechnical Review Board. 2008b. Letter to Mr. Gerry Bordian of MacDonald Development, dated October 14, 2008.
- Clague, J.J., Friele, P.A. and Hutchinson, I. 2003. Chronology and hazards of large debris flows in the Cheekye River Basin, British Columbia, Canada. *Environmental and Engineering Geoscience*, v. 8, pp. 75-91.
- Clague, J.J., Hungr, O. and VanDine, D.F. 2014. Report of the Cheekye River (Ch'kay Staḵw) and Fan Expert Review Panel. Prepared for Province of BC, Squamish Nation, and District of Squamish, April 23, 2014, 49 pp.
- Crippen (Crippen Engineering Ltd.). 1974. Report on Geotechnical-Hydrological Investigation of the Cheekye Fan. Report to BC Department of Housing, Victoria, BC.
- Crippen (Crippen Engineering Ltd.). 1975. Cheekye Fan Development Design Report on Proposed Protection Works. Report to BC Department of Housing, Victoria, BC.
- Crippen (Crippen Engineering Ltd.). 1981. Cheekye Fan Development Report on Hazard Areas and Protective Works. Report to BC Ministry of Lands, Parks and Housing, Victoria, BC.
- CSA (Canadian Standard Association). 2010a. Risk Management – Principles and Guidelines, National Standard of Canada. CAN/CSA-ISO 31000-10, 24 pp.
- CSA (Canadian Standard Association). 2010b. Draft Standard CAN/CSA Q850, Implementation of CAN/CSA-ISO 31000, 2nd Edition of CSA Standard. CAN/CSA Q850-10, 37 pp.
- Direktoratet for Byggekvalitet, Norway. 2015. BYGGEREGLER/Gjeldende-byggeregler/Veiledning-om-tekn.
- District of North Vancouver. 2009. Report to Council: Natural Hazards Risk Tolerance Criteria. District of North Vancouver, BC, November 10, 2009.
- District of Squamish. 2009. Official Community Plan, Bylaw 2100, Section 25 Hazard Lands, District of Squamish, BC.
- Ekes, C. and Friele, P.A. 2003. Sedimentary architecture and post-glacial evolution of Cheekye Fan, southwestern British Columbia, Canada. *In Ground Penetrating Radar in Sediments*, ed. Bristow, C.S. and Jol, H.M. Geological Society of London Special Publication, no. 211, pp. 87-98.
- Ekes, C. and Hickin, E.J. 2001. Ground penetrating radar facies of the paraglacial Cheekye Fan, southwestern British Columbia. *Sedimentary Geology*, v. 143, pp. 199-217.
- Enright, P.R. 2015. Is there a tolerable level of risk from natural landslides in New Zealand? *Georisk*, v. 9, pp.1-8.
- Fell, R., Ho, K.K.S., Lacasse, S. and Leroi, E. 2005. A framework for landslide risk assessment and management. *In Proceedings, Vancouver Geotechnical Conference*, ed. Hungr, O., Fell, R., Couture, R. and Eberhardt, E. Taylor and Francis Group, London.

- Friele, P.A. and Clague, J.J. 2002a. Readvance of glaciers in the British Columbia Coast Mountains at the end of the last glaciation. *Quaternary International*, v. 87, pp. 45-58.
- Friele, P.A. and Clague, J.J. 2002b. Younger Dryas readvance in Squamish River valley, southern Coast Mountains, British Columbia. *Quaternary Science Reviews*, v. 21, pp. 1925-1933.
- Friele, P.A. and Clague, J.J. 2005. Multifaceted hazard assessment of Cheekye Fan, a large debris-flow fan in southwestern British Columbia. *In Debris Flow Hazards and Related Phenomena*, ed. Jakob, M. and Hungr, O. Springer-Praxis, pp. 659-683.
- Friele, P.A. and Clague, J.J. 2009. Paraglacial geomorphology of Quaternary volcanic landscapes in the southern Coast Mountains, British Columbia. *In Periglacial and Pariglacial Processes and Environments*, ed. Knight, J. and Harrison, S. Geological Society of London, Special Publication, no. 320, pp. 219-233.
- Friele, P.A., Ekes, C. and Hickin, E.J. 1999. Evolution of Cheekye fan, Squamish, British Columbia: Holocene sedimentation and implications for hazard assessment. *Canadian Journal of Earth Sciences*, v. 36, pp. 2023-2031.
- GEO (Geotechnical Engineering Office, Hong Kong Government). 1998. Landslides and Boulder Falls from Natural Terrain: Interim Risk Guidelines. Government of the Hong Kong Special Administrative Region, Geotechnical Engineering Office, GEO Report No.75.
- Golder Associates Ltd. 2013. Cheekye Fan Hazard Review. Report to BC Ministry of Forests, Lands and Natural Resource Operations, Victoria, BC.
- Hand, D. 2000. Report on the Inquest into the Deaths Arising from the Thredbo Landslide. Coroner's Report, New South Wales, Australia.
- HSE (United Kingdom Health and Safety Executive). 2001. Reducing Risk, Protecting People, HSE Decision-making Process. HM Stationery Office, London.
- Hungr, O., 1997. Some methods of landslide hazard intensity mapping. *In Proceedings, Landslide Risk Workshop*, ed. Fell, R. and Cruden, D.M. Balkema, Rotterdam, pp. 215-226.
- Hungr, O. and Rawlings, G. 1995. Assessment of terrain hazards for planning purposes: Cheekye fan, British Columbia. *In Proceedings of the Canadian Geotechnical Conference 1995*. Vancouver, BC, pp. 509-517.
- ICOLD (International Commission on Large Dams). 2003. Risk Assessment in Dam Safety Management, Draft ICOLD Bulletin. International Commission on Large Dams, Paris.
- ISO (International Organization for Standardization). 2009. Risk Management – Principles and Guidelines. ISO 31000, 24 pp.
- Jakob, M. and Friele, P.A. 2010. Frequency and magnitude of debris flows on Cheekye River, British Columbia. *Geomorphology*, v. 114, pp. 382–395.
- Jakob, M., McDougall, S., Weatherly, H. and Ripley, N. 2012. Debris-flow simulations on Cheekye River, British Columbia. *Landslides*, published online November 10, 2012.
- Jones, W.C. 1959. Cheekye River Mudflows. BC Department of Mines, Victoria, BC, 9 pp.
- KWL (Kerr Wood Leidal Associates Ltd.). 2003. Preliminary Design Report for Cheekye Fan Deflection Berms. Report for District of Squamish, Squamish, BC.
- KWL (Kerr Wood Leidal Associates Ltd.) 2007. Flood and Debris Flow Mitigation Strategy for Cheekye Fan, Squamish, BC. Draft Report for the Cheekye River Development Limited Partnership, 31 pp.

- Lateltin, O. 1997. Naturgefahren. Berücksichtigung der Massenbewegungsgefahren bei raumwirksamen Tätigkeiten Empfehlungen. Bundesamt für Raumplanung BRP, Bundesamt für Wasserwirtschaft BWB, Bundesamt für Umwelt, Wald und Landschaft BUWAL, Bern, Switzerland (in German and French).
- Lateltin, O., Haemmig, C., Raetzo, H. and Bonnard, C. 2005. Landslide risk management in Switzerland. *Landslides*, v. 2, pp. 313–320
- Leroi, E., Bonnard, C., Fell, R. and McInnes, R. 2005. Risk assessment and management. *in* Proceedings of International Conference on Landslide Risk Management, ed. Hungr, O. Fell, R., Couture, R. and Eberhardt, E. Balkema, pp. 159-198.
- Macciotta, R. 2013. Quantitative Risk Assessment of Natural and Cut Slopes: Measuring Uncertainty in the Estimated Risks and Proposed Framework for Developing Risk Evaluation Criteria. Ph.D. thesis, University of Alberta, Edmonton, AB, 186 pp.
- Malone, A.W. 2005. The story of quantified risk and its place in slope stability policy in Hong Kong. Chapter 22 *in* Landslide Hazard and Risk, ed. Glade, T., Anderson, M.G. and Crozier, M.J. John Wiley & Sons Ltd., pp. 643-674.
- Mathews, W.H. 1952. Mount Garibaldi, a supraglacial Pleistocene volcano in southwestern British Columbia. *American Journal of Science*, v. 250, p. 553–565.
- Mathews, W.H. 1958. Geology of the Mount Garibaldi map area, southwestern British Columbia, Canada. Part II: Geomorphology and Quaternary volcanic rocks. *Geological Society of America Bulletin*, v. 69, pp. 179–198.
- Morgan, G.C. 1991. Cheekye River Fan – Terrain Hazard Assessment. Report to Dr. D. Kasianchuk, Waste Management Division, BC Ministry of Environment.
- Morgan, G.C. 1992. Quantification of risks from slope hazards. *In* Proceedings of the Geological Hazards Workshop, Victoria, BC, ed. Bobrowsky, P.T. BC Geological Survey Branch, Open File 1992-15, pp. 57-70.
- Morgenstern, N.R. 1995. Managing risk in geotechnical engineering. The 3rd Casagrande lecture. *In* Proceedings 10th Pan-American Conference on Soil Mechanics and Foundation Engineering, Guadalajara, Mexico, v. 4, pp. 102-126.
- NBCC (National Building Code of Canada). 1995. Published by the National Research Council of Canada, Ottawa, ON.
- NBCC (National Building Code of Canada). 2005. Published by the National Research Council of Canada, Ottawa, ON.
- OFAT. 1997. Prise en Compte des Dangers dus aux Mouvements de Terrain dans le Cadre de l'aménagement du Territoire (Consideration of Landslide Hazards in Land-use Practice), Recommendations, Office fédéral de l'aménagement du territoire (OFAT), Office fédéral de l'économie des eaux (OFEE), Office fédéral de l'environnement, des forêts et du paysage (OFEFP). OCFIM Nr. 310.023f, Berne, Switzerland (in French; German version also available).
- OFEFP (Office fédéral de l'environnement, des forêts et du paysage). 1996. Critères d'appréciation pour l'ordonnance sur les accidents majeurs.
- OFEV (Office fédéral de l'environnement). 2011. Fondements juridiques de la gestion intégrée des risques en matière de protection contre les dangers naturels. Avis de droit.
- Pierce County. 2014. Volcanic Hazard Areas, Chapter 18E.60, Title 18E, Pierce County (Washington) Code, adopted 2004—Ordinance No. 2004–57s, 2014 edition.
- Pierson, T.C., Wood, N.J. and Driedger, C.L. 2014. Reducing risk from lahar hazards: Concepts, case studies, and roles for scientists. *Journal of Applied Volcanology*, v. 3, pp. 16.

- PLANAT. 2014. Security Level for Natural Hazards. National Platform for Natural Hazards, Federal Office for the Environment, Berne, Switzerland.
- Porter, M. and Morgenstern, N.R. 2013. Landslide risk evaluation. *In* Canadian Technical Guidelines and Best Practices Related to Landslides: A National Initiative for Loss Reduction. Geological Survey of Canada, Open File 7312
- Porter, M., Jakob, M. and Holm, K. 2009. Proposed landslide risk tolerance criteria. *In* Proceedings of the Canadian Geotechnical Conference 2009, Halifax, NS, Paper 75, 9 pp.
- Porter, M., Jakob, M, Savigny, K.W., Fougere, S. and Morgenstern, N. 2007. Risk management for urban flow slides in North Vancouver, Canada. *In* Proceedings of the Canadian Geotechnical Conference 2007, Ottawa, ON, Paper 95, 9 pp.
- Rasmussen, N.C. 1975. Reactor Safety Study: An Assessment of Accident Risk in US Commercial Nuclear Power Plants. U.S. Nuclear Regulatory Commission, WASH-1400 NUREG 75/014, Washington, DC.
- Sobkowicz, J., Hungr, O. and Morgan, G. 1995. Probabilistic mapping of a debris flow hazard area: Cheekye Fan, British Columbia. *In* Proceedings of the Canadian Geotechnical Conference 1995, Vancouver, BC, pp. 519-529.
- TEL-GAL (Thurber Engineering-Golder Associates). 1993. The Cheekye River Terrain Hazard and Land-Use Study; Final Report, Volumes 1 and 2. Report to BC Ministry of Environment, Lands and Parks, Burnaby, BC.
- Tappenden, K.M. 2014. The District of North Vancouver's landslide management strategy: Role of public involvement for determining tolerable risk and increasing community resilience. *Natural Hazards*, v. 72, pp 481-501.
- Town of Canmore, 2015. Cougar Creek Long-Term Mitigation, Option Analysis Summary Report. January 13, 2015.
- US Army Corps of Engineers. 2008. Safety of Dams – Policy and Procedures. ER-1110-2-1156.
- US Bureau of Reclamation. 2012. Risk Guidelines. US Bureau of Reclamation Dam Safety Office, Denver, CO (website document).
- VanDine, D.F. 2012. Risk Management – Canadian Technical Guidelines and Best Practices Related to Landslides. Geological Survey of Canada, Open File 6996, 8 pp.
- VanDine, D.F. and Lister, D.L. 2011. The much misunderstood 1:475 landslide. *In* Proceedings of the 5th Canadian Conference on Geotechnique and Natural Hazards, Kelowna, BC, Paper 179.
- Vick, S.G. 2002. Degrees of Belief: Subjective Probability and Engineering Judgment. American Society of Civil Engineers, 455 p.
- Vulliet, L. and Bonnard, C. 1996. The Chlowena Landslide: Prediction with a viscous model. *In* Proceedings of the 7th International Symposium on Landslides, Trondheim, v. 1, pp. 397–402.
- Wong, H.N. 2005. Landslide risk assessment for individual facilities. *In* Landslide Risk Management, ed. Hungr, O., Fell, R., Couture, R. and Eberhardt, E. Proceedings, Vancouver Conference. Taylor and Francis Group, London.

Glossary of Some Technical Terms Used in this Report

Acceptable risk Risk that society is prepared to accept and for which no risk reduction is required.

Avulsion A sudden shift in the channel of a stream or river.

Consequence Outcome of a hazardous event that adversely affects human health and safety, property, aspects of the environmental, and/or financial interests; can be expressed qualitatively or quantitatively.

Debris flood High-velocity flow that is transitional between a stream flood and a debris flow.

Debris flow High-velocity, destructive, surging flow of water-saturated sediment ranging in size from clay to boulders, including trees and other vegetation.

Elements at risk Objects or assets such as human health and safety, property, aspects of the environment, and/or financial interests that can be adversely affected (by a landslide).

Group risk Also referred to as societal risk. Risk to a group of individuals from a hazard.

Hazard Event, such as a landslide, that can have a harmful effect on people, the environment, or the economy.

Hazard probability Probability of a hazardous event occurring.

Hazard probability tolerance criteria Thresholds beyond which the estimated probability of a hazardous event occurring is considered unacceptable.

Individual risk Risk to a specific person from a hazard, When referring to the specific person who is most exposed to the risk, individual risk is termed personal individual risk (PIR).

Landslide Downward and outward movement of a body of rock or soil under the influence of gravity.

Lahar Debris flow associated with volcanoes and volcanic activity.

Mitigation (also treatment or reduction) Process of reducing the risk or hazard probability by, for example engineered structures or avoidance.

Natural hazard A natural event that can have a harmful effect on people, the environment or the economy.

Pyroclastic deposit An accumulation of volcanic material blown from a volcano during an explosive eruption; the material ranges from ash particles to blocks and 'bombs'.

Quantitative risk assessment Process of analyzing and evaluating risk using numerical values or ranges of values of the hazard probability and consequences to determine whether risk is tolerable.

Residual risk Risk remaining i) from not considering hazards that are less probable, and therefore from not considering larger landslides, and ii) after risk mitigation; includes previously unidentified risks.

Return period Statistically, the inverse of annual probability of an event occurring.

Risk Product of the likelihood or probability that an event, such as a landslide, will occur and the expected consequence if the event does occur.

Risk tolerance criteria Thresholds beyond which the estimated risk is considered unacceptable.

Societal risk Also referred to as group risk. Risk to a group of individuals from a hazard.

Stakeholders Persons or organizations that can affect, be affected by, or perceive themselves to be affected (by a landslide), or by associated decisions or activities, including appropriate government agencies.

Tolerable risk Risk that that society can live with so as to secure net benefits; tolerable risk is regarded as non-negligible and must be reviewed and reduced further if possible.

Appendix A

Portion of Terms of Reference (Introduction, Panel Composition, and Scope of Review) for Panel #2, March 25, 2015

Introduction

The Province of BC, Squamish Nation and its Partnership, and District of Squamish collectively have formed and will collaborate with an Expert Review Panel to review relevant background information on the appropriate risk tolerance criteria established with respect to the mitigation of debris flow hazard on the Cheekye Fan in preparation of a report with key findings and recommendations.

Panel Composition

The Expert Review Panel will leverage the previous Landslide Hazard and Risk Assessment panel members, to ensure a seamless transition of the information garnered from the original panel's findings. The panel will have access to and be augmented with risk criteria specialists as required. The expert panel members shall not include the authors of studies submitted in support of the Official Community Plan amendment application submitted to the District, but may include previous reviewers independent from BGC Engineering Inc and Kerr Wood Leidal Associates.

The expert panel members will be selected on the basis of having meaningful contributions to the field of debris hazard, risk assessment and risk tolerance criteria, and/or their associated expertise in this field. Panel members should have the following qualifications:

- at least 20 years of experience in the field of risk tolerance criteria, and debris flow hazard and risk assessments
- PhD, M.Sc. or M.Eng. and be registered with APEGBC, or equivalent
- Ample experience nationally and/or internationally on topics of landslide risk, and the establishment and application of municipal risk tolerance criteria associated with these phenomena
- An understanding of the historical evolution of hazard and risk tolerance criteria in British Columbia and international jurisdictions
- An understanding of debris-flow processes in British Columbia, including landslides in volcanic terrain, with at least some familiarity of the Cheekye Fan situation

Based on the criteria above, the following individuals are nominated for the panel:

- John Clague – Chair
- Douglas VanDine
- Oldrich Hungr
- Norbert Morgenstern

Scope of Review

The Panel will utilize the recommendations of the earlier "Cheekye River and Fan Expert Review Panel" with respect to the frequency and magnitude of the debris flows being considered on the Cheekye Fan, and further review scientific and engineering reports and other risk tolerance criteria information provided by the Province, the District of Squamish and the Squamish Nation and its

Partnership. This will not preclude the panel, at its discretion, to review additional information that is otherwise accessible and relevant for its findings.

The Panel will assist stakeholders in:

- advising risk tolerance criteria for existing and proposed new development on Cheekye Fan based on criteria adopted by other municipal, regional, and provincial agencies in British Columbia and/or elsewhere
- advising on current levels of individual and group risk on Cheekye Fan for landslides/debris flows/debris floods
- advising on individual and group risk reduction that might be achieved, given current and proposed new development, through remediation
- advising on whether group and individual risk tolerance criteria are best applied to landslides/debris flows/debris floods across the municipality or solely to the Cheekye Fan area.

Appendix B

Curricula Vitae of the Panel #2 Members

John J Clague P.Geo., Ph.D.

Professor and CRC Chair in Natural Hazard Research
Director, Centre for Natural Hazard Research
Department of Earth Sciences, Simon Fraser University, Burnaby, BC

EDUCATION

Ph.D., geology, University of British Columbia, Vancouver, BC, 1973
M.A., geology, University of California, Berkeley, California, 1969
A.B. magna cum laude, Occidental College, Los Angeles, California, 1967

AREAS OF EXPERTISE

Quaternary geology, geomorphology, engineering geology, environmental geology, sedimentology, stratigraphy, neotectonics, paleoseismology, natural hazards.

CONTRIBUTION AND IMPACT

One of Canada's leading authorities in Quaternary and environmental earth sciences; 40-years' experience in surficial/terrain mapping, Quaternary stratigraphic investigations, engineering and environmental interpretations of surficial geological information, and natural hazard studies; noted for local, national, and international research collaboration with other geologists, geographers, biologists, and physicists.

Dr. Clague has published over 300 papers, reports, and monographs on a wide range of earth science topics of regional and national importance; his papers have appeared in 50 different international journals; prepared innovative geoscience products for educators and the public; He has given numerous television and radio interviews and newspaper and magazine article; research on earthquakes, landslides, and floods has greatly increased public and official awareness of these hazards.

PROFESSIONAL SERVICE

President, Association of Professional Engineers and Geoscientists of the Province of BC (APEGBC); Former Editor-in-Chief of the *Canadian Journal of Earth Sciences*; former President of the Geological Association of Canada; former President of the Canadian Geoscience Education Network (CGEN); former President of the Canadian Geomorphology Research Group; former President of the International Union for Quaternary Research (INQUA); member of numerous national and international professional committees and commissions; Adjunct Professor - University of Fraser Valley, University of Northern BC, and University of Victoria; Associate Faculty – SFU Department of Archaeology and the School of Resource and Environmental Management (Cooperative Resource Management Institute). Serves on many graduate student committees at Simon Fraser University and the University of British Columbia; has given about 400 lectures at North American universities, professional meetings, and public venues, and reviewed scores of papers for scientific journals.

PROFESSIONAL EMPLOYMENT HISTORY

- 2003-present, Tier I Canada Research Chair in Natural Hazard Research
- 1998-present, Professor, Earth Sciences, Simon Fraser University
- 2009-present, Adjunct Professor, University of Victoria
- 2009-present, Adjunct Professor, University of Fraser Valley
- 2008-present, Adjunct Professor, University of Northern British Columbia
- 1974-1998, Research Scientist, Geological Survey of Canada
- 1996-1998, Adjunct Professor, Earth Sciences, Simon Fraser University
- 1988-1992, Editor-in-Chief, Canadian Journal of Earth Sciences, National Research Council of Canada
- 1973-1974, NSERC Postdoctoral Fellow, Geological Survey of Canada, Vancouver

POSITIONS IN SOCIETIES

- President, International Union for Quaternary Research, 2003-2007
- President, Geological Association of Canada, 2002
- Education Director, Canadian Geoscience Council, 2001-2002
- President, Canadian Geoscience Education Network, 2001-2002
- Vice-President, Geological Association of Canada, 2001
- Vice-President, International Union for Quaternary Research, 1999
- President, Canadian Geomorphology Research Group, 1998
- Vice-President, Canadian Geomorphology Research Group, 1997
- Vice-President, Canadian Quaternary Association, 1985-1987
- Councillor, Canadian Quaternary Association, 1984

EDITORSHIPS

- Associate Editor, *Journal of Quaternary Sciences*, 2006-present
- Associate Editor, *Quaternary International*, 2003-present
- Associate Editor, *Quaternary Science Reviews*, 2008-present
- Associate Editor, *Canadian Journal of Earth Sciences*, 1983-1988
- Editor-in-Chief, *Canadian Journal of Earth Sciences*, 1988-1992

PROFESSIONAL AFFILIATIONS

- Professional Geologist, Association of Professional Engineers and Geoscientists of British Columbia
- Fellow, Geological Society of America
- Fellow, Geological Association of Canada
- Member, American Geophysical Union
- Member, Canadian Geophysical Union
- Member, American Quaternary Association
- Member, Canadian Quaternary Association
- Member, Vancouver Geotechnical Society
- Member, Association of Earth Science Editors

Oldrich Hungr P.Eng./P.Geo., Ph.D.

Professor, Engineering Geology, Geological Engineering Program
Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, BC

EDUCATION

B.A.Sc., Civil Engineering, Geotechnical, University of Ottawa, 1972.

M.A.Sc., Civil Engineering, Geotechnical, University of Ottawa. 1975.

Ph.D., Civil Engineering, Geotechnical, University of Alberta, 1981.

EMPLOYMENT

1996-present: Professor of Engineering Geology, University of British Columbia

1981-1996: Associate and Senior Geotechnical Engineer, Thurber Engineering Ltd.,
Vancouver, BC

1975-1977: Geotechnical Engineer, The Trow Group, Toronto, Ontario

SELECTED PROJECT EXPERIENCE

Over 1000 geotechnical and engineering geology assignments, including:

Review Boards:

- Member, Slope Safety Technical Review Board, Hong Kong, 2006-2009
- Member, internal review panel for the Site C reservoir hazard studies, BC Hydro.
- Member, Value Engineering Panel for the Fountain Slide, Fraser Valley. Ministry of Transportation, BC
- External Reviewer: Professional Practice Guidelines for Landslide Hazard Assessment in Residential Areas. Association of Professional Engineers and Geoscientists, British Columbia.
- Member of an advisory panel considering the stability and failure consequences for the 600m high South Spoil waste pile. Fording Coal, Elkford.
- Review Panel, waste pile stability, Porgera Mine, Papua New Guinea.
- Review Panel, rock avalanche hazard assessment, Britannia, British Columbia

Engineering geological studies for community planning:

- Development of a risk assessment framework for conducting geotechnical feasibility studies, Hong Kong Housing Authority.
- Quantitative risk analysis of landslide hazards, Geotechnical Eng. Office, Hong Kong.
- Overview study of landslide hazard zonation, Ryder Upland, Reg. District of Fraser Cheam, BC
- Natural hazard zoning map, Greater Vancouver Regional District Water Supply Department.
- Engineering geology overview map, City of Sault Ste. Marie, Ontario

Site investigations and hazard assessments for roads and railways:

- Review of rock cut stabilization measures in selected sections, Vancouver-Whistler highway upgrade.
- Detailed assessment of debris flow hazards, BC Highway 99, Vancouver to Squamish.
- CP Rail Beaver Valley track twinning, Glacier National Park - design of 16 km of rock cuts along the eastern approach to the Mt. MacDonald tunnel.

- Slope stability assessment, Beaton River connector, Fort St. John, BC - route crossing numerous active landslide areas in Cretaceous shales.

- Route selection and feasibility study, Trans-Canada Highway, Golden to Yoho, BC

Pipelines and transmission lines:

- Feasibility study, Trans-Adriatic Gas pipeline, Albania.
- Hazard assessment for contingency planning, Trans-Mountain Pipeline, Edmonton to Vancouver.
- Natural hazards mapping and route selection, Kemano Transmission line, Kitimat, BC

Dams and Reservoirs:

- Slope stability review, BC Hydro Site "1" reservoir, Peace River.
- 3D slope stability assessment, BC Hydro Hart Dam, Vancouver Island.
- Slope stability assessment, BC Hydro proposed Site "C" reservoir, Peace River, and Beavercrow reservoir, Liard River, including an assessment of the potential for slide - induced waves.

Landslide hazard studies:

- Silverhope area hazards study, BC - hazard zoning of an area subject to rockfall and rockslides.
- Cheekye Fan terrain hazard study, Squamish - detailed engineering geological mapping of an area of Quaternary volcanics, probabilistic hazard and risk assessment for planning.
- Scoping study of a landslide Quantitative Risk Assessment (QRA) in Hong Kong.
- Review consultant, Natural Terrain Hazard Study, Pat Heung, Hong Kong.
- Landslide hazard assessment, Prince Rupert Container Terminal, British Columbia

Geotechnical aspects of waste disposal:

- Assessment of behaviour in the event of failure, Syncrude Canada Ltd. Mildred Lake tailings dyke, Fort McMurray, Alberta.
- Liquefaction flow study, Sand Storage Facility, Syncrude, Fort McMurray, Alberta
- Review of stability, potential slide behaviour and remedial measures, coarse spoil storage, Suncor oil sand mine, Fort McMurray, Alberta.
- Analysis of potential failure behaviour of waste pile slides, Grasberg Mine, Indonesia.
- Waste pile stabilization and hazard assessment, Questa Molybdenum Mine, New Mexico.

Landslide stabilization:

- Stabilization of a 200,000 m³ Bentley Rockslide on Highway 97, Peachland, BC
- Feasibility study of stabilization measures, Attachie Slide, proposed BC Hydro "Site C" reservoir.
- Stability assessment and unloading stabilization design (15 million tons) for a large landslide at the Placer Dome Golden Sunlight Mine, Butte, Montana.

Landslide protection works:

- Engineering geology input into the design of debris flow protection structures, Squamish Highway - barriers, passage channels, bridges.
- Debris flow hazards assessment and design of defensive measures, Coquihalla Highway, Hope to Merritt - 12 retention basins and deflecting dykes.
- Design of a debris flow protective barrier, Tsin Yan housing development, Hong Kong.
- Dynamic analysis, debris flow structure at Sham Tseng San Tsuen Village, Hong Kong.
- Debris flow hazard assessment and design of protective barriers, Whistler, BC
- Design review, MacKay creek debris flow protection structure, North Vancouver.
- External review, Standard Barrier Design Development Study, GEO, Hong Kong
- Hazard assessment and protective measures, East Gate landslide, Glacier Park, Canada.

- Review consultant, debris avalanche protection measures for three sites, Hong Kong.
- Preliminary design of debris flow/avalanche protection, Prince Rupert Container Terminal, B. C.

Excavations:

- Highwall slope design, Gulf Canada Obed-Marsh coal mine, Hinton, Alberta.
- Pit landslide stability assessment, Cardinal Coal, Red Deer, Alberta.
- Robson Place building excavation, downtown Vancouver- design and monitoring.

Tunnels:

- Site investigation for the 15 km MacDonald Tunnel in Rogers Pass, BC, including a 300 m deep ventilation shaft.
- Site investigation for the North Diversion tunnel, Riyadh, Saudi Arabia.
- Site investigation for the 3 km power tunnel at Mamquam, north of Vancouver, BC
- Design review of tunnel modifications and station caverns, Vancouver rapid transit.

Expert testimony:

- Expert witness representing the BC Ministry of Highways and other parties in five separate cases involving fatalities and injuries caused by rockfall on BC highways.
- Testimony regarding the influence of logging on triggering a debris flow, Vancouver, BC
- Expert testimony regarding a rock fall accident near Larissa, Greece.
- Expert testimony regarding a major fatal landslide accident in Papua New Guinea.

SELECTED PROFESSIONAL ACTIVITIES

- Registered Professional Engineer / Geoscientist of British Columbia (P.Eng./P.Geo.)
- Member, Association of Professional Engineers and Geoscientists (APEGBC Board of Examiners.
- Member of the Editorial Board, Engineering Geology, Elsevier, Amsterdam
- Associate Editor, "Landslides", Journal of the International Landslide Consortium, Kyoto, Japan.
- North American Representative – IASMG, IAEG and ISRM Joint Technical Committee on Landslides and Engineered Slopes
- Canadian Representative, UNESCO-Kyoto University "Round Table for Landslide Hazards Mitigation", 3 day meeting, Tokyo, January, 2006.
- Chair, Task force on the promotion of geological engineering and engineering geology in Canada, Canadian Geotechnical Society, Engineering Geology Division, 2001-2002.

INVITED AND KEYNOTE LECTURES

- Keynote speaker, ROCEXS-2011, International Workshop on Rock Fall Hazard Engineering, Innsbruck, Austria, May 2011.
- Keynote speaker, 5th International Conference on Debris Flows, Padova, Italy, July 2011.
- Coordinator, Benchmarking Exercise on Landslide Dynamics at the International Forum on Landslide Management, Hong Kong, December, 2007
- Invited speaker, JTC-1 ("Joint Technical Committee on Landslides") Workshop on Mechanics and Velocity of Large Landslides, Courmayeur, Italy, September 25-29, 2006.
- Invited speaker, Workshop on guidelines for landslide susceptibility, hazard and risk zoning, 18th to 21th September 2006, Technical University of Catalonia, Barcelona, Spain
- Invited lecture, Hong Kong Institution of Civil Engineers (December 2006)
- State-of-the-Art Lecture, Theme 5, Int. Conference on Landslide Risk Management, Vancouver, May 2005.

- 57th Canadian Geotechnical Conference, Quebec City, October 2004
- NATO Advanced Workshop on Landslide Dams, Bishkek, Kyrgyzstan, July 2004.
- "Flows 2003", International Conference, Sorrento, Italy, June 2003.
- "Natural Terrain Hazards, a Constraint to Development?" Annual Meeting of the Institution of Mining and Metallurgy, Hong Kong Branch, Hong Kong, November 2002.
- NATO Advanced Workshop on Massive Slope Failure, Celano, Italy, June 2002.
- Workshop on Landslide Hazards and Risk Management in Canada, Geological Survey of Canada. Ottawa, November 16-18, 2001
- Co-Author, State-of-the-Art Lecture "Cuts and Fills in Soil" at the GeoEng 2000, International Conference on Geotechnical and Geological Engineering in Melbourne, November 2000.
- Second Pan-American Symposium on Landslides, Rio de Janeiro, November 1997.

AWARDS AND HONOURS

- Fellow, Geological Society of America (2010)
- Meritorious Achievement Award, BC Association of professional Engineers and Geoscientists (2010)
- Geological Society of America Burwell Award in Engineering Geology (2009)
- Schuster Medal awarded jointly by the US Association of Environmental & Engineering Geologists and the Canadian Geotechnical Society. This medal recognizes excellence in research on geohazards (2008)
- Fellow, Engineering Institute of Canada (2008)
- Visiting Foreign Researcher Award, Institut de Physique du Globe de Paris
- Earth and Ocean Sciences, UBC, Faculty Teaching Prize (2006).
- "Innovation" Editorial Board Award, Association of Professional Engineers and Geoscientists of BC (2005).
- Association of Engineering Geologists (US) AEG Publication Award (2001).
- The Canadian Geotechnical Society Prize (1995).
- The Thomas Roy Award, Engineering Geology Division, Canadian Geotechnical Society (1990).
- Member of a project team that received the Canadian Consulting Engineering Award of Merit for the design of a series of debris flow protection structures near Vancouver (1986).
- Research Award for Foreign Specialists, Science and Technology Agency, Japan (1989).
- Canada - France Science and Technology Cooperation Program Award (1990).

TEACHING

UBC courses:

- Third and fourth year courses on Geological Engineering, Geomorphology and Field School, graduate course on Advanced Geotechnics, Coordination of B.A.Sc. theses.

Short courses on landslide hazards engineering:

- Vienna Polytechnic, Austria, 2010
- Milano Polytechnic, Italy, 2009
- APEGBC, Vancouver, 2006 and 2008)
- University of Rome La Sapienza, July 2005 and April 2006
- ETH Zurich, April 2006
- Washington State Department of Transportation, Seattle, September 2004
- Vienna Polytechnical Institute, Austria, May 2003

- University of Taranto, Italy, June 2003
- Slope stability and runout analysis training course, Freeport Grasberg Mine, Indonesia, April 2010
- Short course on landslide hazard assessment, Geological Survey of Canada project "Geoscience for Andean Communities, Mendoza, Argentina and Caracas, Venezuela. Oct. 2003, February 2004
- Seminar on slope stability analysis, Syncrude Canada Ltd., Fort McMurray, December 1990

SELECTED SERVICE TO THE UNIVERSITY

- Mentor, E. Eberhardt
- Director of the Geological Engineering Program (from August 1, 1998 to August 1, 2002)
- Geological Engineering Student Advisor (1998-2002)
- Chair of the Board of Study (1996-2002)
- Chair of an ad hoc committee preparing a curriculum change to eliminate options from the Geological Engineering program (2001-2002)
- Department representative, Graduate Council (since September 2003)
- Ex Officio Member, Head's Advisory Committee, 1998-2000

CONFERENCE ORGANIZATION

- Member of the Technical Committee, 2012 International Symposium on Landslides, Banff.
- Member of the Organizing Committee, Chair, Scientific Program Committee, Vancouver Conference on Landslide Risk Management, 2005
- Co-Chair, Scientific Program Committee, Member of the Organizing Committee and field trip leader, 8th Congress of the International Assoc. of Engineering Geology, Vancouver, BC, September 1998
- Member of the Organizing Committee, Chair of the Papers Subcommittee, 48th. Canadian Geotechnical Conference, Vancouver, BC, September 1995

PUBLICATIONS

Dr. Hungr has authored or co-authored over 300 refereed papers, conference papers and presentations, major reports, book reviews and edited a number of technical book. A listing of these is available upon request.

Norbert R. Morgenstern P.Eng., Ph.D.

University Professor (Emeritus) of Civil Engineering,

Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta

EDUCATION

B.A.Sc.	(Civil Engineering)	University of Toronto	1956
D.I.C.	(Soil Mechanics)	Imperial College of Science and Technology	1964
Ph.D.	(Soil Mechanics)	University of London	1964
D.Eng.	(h.c.)	University of Toronto	1983
D.Sc.	(h.c.)	Queen's University	1989

EXPERIENCE

1956	Geocon Ltd.
1957-1958	Graduate Studies, Imperial College of Science and Technology
1958-1960	Research Assistant, Imperial College of Science and Technology
1960-1968	Lecturer in Civil Engineering, Imperial College of Science and Technology
1968 to 1983	Professor of Civil Engineering, University of Alberta
1983 to 1999	University Professor of Civil Engineering, University of Alberta
1999 to present	University Professor (Emeritus) of Civil Engineering, University of Alberta
1994 to 1997	Chair, Department of Civil and Environmental Engineering, University of Alberta
1961 to present	Advisor to consulting engineers and public agencies on a variety of problems in Engineering Earth Sciences, examples below.

PROFESSIONAL AFFILIATIONS

Association of Professional Engineers of Alberta
 Association of Professional Engineers and Geoscientists of British Columbia
 Engineering Institute of Canada
 Canadian Committee on Large Dams
 Association of Engineering Geologists
 Geological Society of London
 British Geotechnical Society
 American Society of Civil Engineers
 International Society for Rock Mechanics
 International Society for Soil Mechanics and Foundation Engineering
 Canadian Geotechnical Society
 Canadian Institute for Mining and Metallurgy
 International Association for Engineering Geologists
 Canadian Society for Civil Engineering
 Royal Society of Canada
 Canadian Academy of Engineering
 National Academy of Engineering, U.S.A.
 Royal Academy of Engineering, United Kingdom
 National Academy of Engineering, India

SELECTED CONSULTING ENGAGEMENTS

Landslides and Slope Stability (Soil, Rock and Permafrost)
Department of Water Development, Republic of Cyprus
Soil Mechanics Ltd., United Kingdom
Freeman, Fox and Partners, United Kingdom
Marples Ridgway Ltd., United Kingdom
Kent County Council, United Kingdom
U.S. Atomic Energy Commission, United States
Sir Bruce White, Wolfe Barry and Partners, Malaysia
United States Army Corps of Engineers, United States
Syncrude Project, Canada
Department of Energy, Mines and Resources, Canada
City of Edmonton, Canada
Cassiar Asbestos Corporation
R.M. Hardy and Associates, Canada
Department of Highways, British Columbia, Canada
Milner and Steer, Canada
Geotecnica S.A., Brazil
Government of Hong Kong
Thurber Consultants Ltd., Canada
Montreal Engineering Co. Ltd. - Anandekaleka Project, Madagascar
City of Calgary, Canada
Golder Associates Ltd., Canada
Union Oil Company, Canada
Amoco Oil Company, USA
Denver and Rio Grande Railway, USA
Montreal Engineering Co. Ltd. - Electricity Trust of S. Australia, Australia
Alexander Holburn, Canada
City of Ft. McMurray, Canada
Alberta Transportation, Canada
Leigh Creek Mine, Australia
Panama Canal Commission, Panama
OK Tedi Mining Ltd., Papua New Guinea
Dyregrov and Burgess, Canada
Ware and Freidenrich, USA
SNC Inc., Canada
Icelandic Civil Defence, Iceland
The OSLO Project, Canada
Porgera Mine (Placer Dome), Papua New Guinea
Department of Environment, British Columbia, Canada
BC Hydro, Canada
CP Rail Systems, Canada
RKTG Consultants, USA
IRMS Ltd., Canada
City of Nanaimo, Canada
Osler, Hoskin and Harcourt, Canada
City of Lethbridge, Canada

Bentall Corporation, Canada
 Singleton, Urquhart and Associates, Canada
 Golden Cross Mine, New Zealand
 Phosphogypsum Stack, Fosfertil, Brazil
 Shapiro, Hankinson and Knutsoon, Canada
 Town of Quesnel, Canada
 Trans Colorado Pipeline, USA
 Oahe Reservoir, US Dept. Of Justice
 Highland Valley Mine, Canada
 Chilliwack Development, Canada
 Waste Dump Stability, Molycorp, USA
 McGregor Dam Slide, Klohn Crippen, Canada
 North Vancouver Flowslide, Municipality of North Vancouver and Singleton Urquhart
 Waste Dumps, Anaina-CODELCO, Chile
 Mira Mesa Mine, CODELO Norte, Chile
 Cheekye Fan Development, Canada
 Codelco Waste Dumps, Chile
 Dielman Pit Stability, Cameco, Canada
 Marandoo Pit Slopes, Australia

OTHER TECHNICAL ACTIVITIES

1959	Member, Imperial College glaciological expedition to Austerdalsbre, Norway.
1963	Member, Royal Society, Institution of Civil Engineers mission to Skopje, Yugoslavia to report on earthquake effects.
1964 to 1997	Member, Editorial Board of International Journal of Rock Mechanics and Mining Sciences.
1970 to 1976	Member, Editorial Board of Journal of Soil Mechanics and Foundations, American Society of Civil Engineers.
1970 to 1976	Member, Canadian Advisory Committee on Rock Mechanics, Department of Energy, Mines and Resources.
1971 to 1975	Member, UNESCO Committee of Experts on Strong Motion Seismology.
1971 to 1978	Member, Associate Committee for Geotechnical Research, National Research Council of Canada.
1972 to 1976	Member, Canadian National Committee for Earthquake Engineering.
1972 to 1976	Member, Publications Committee, ASCE, Geotechnical Engineering Division.
1973 to 1980	Member, Engineering Geology Committee, ASCE, Geotechnical Engineering Division.
1973 to 1976	Member, Earth Sciences Grant Selection Committee, National Research Council of Canada; Chairman, 1975-76
1973 to 1981	Member, Editorial Board, Bulletin of Association of Engineering Geologists.
1974 to 1984	Member, Embankment Dams and Slopes Committee, ASCE, Geotechnical Engineering Division.
1974 to 1978	Member, Organizing Committee, 3rd International Congress on Permafrost; Chairman, Technical Program Sub-Committee.
1975 to 1978	Member, Editorial Board, Earth Surface Processes.
1975 to 1977	Member, Editorial Board, Canadian Geoscience Council.
1975	Member, Alberta Mission to Europe.

1977	Member, Canadian Permafrost Delegation to China.
1977 to 1981	Member, University Evaluation Panel, Alberta Oil Sands Technology and Research Authority.
1978 to 1979	Member, Organizing Committee, Canadian Conference on Marine Geotechnical Engineering.
1978	Chairman, Conference on Industrial Research and Development in Alberta.
1978 to 1980	Member, Technical Sub-Committee on Slope Stability, Canadian Geotechnical Society.
1978	Member, Ad Hoc Review Committee, Geotechnical Program, University of California, Berkeley.
1978 to 1980	Member, Sub-Committee on Tailings Dams, Canadian National Committee on Large Dams.
1979 to 1981	Member, Sub-Committee on Soil and Rock Engineering, Associate Committee for Geotechnical Research, National Research Council.
1980	Member, Ad Hoc Review Committee on Geotechnical Research, National Research Council.
1980	Member, Natural Sciences and Engineering Research Council of Canada, Task Force on Equipment.
1980	Chairman, APEGGA Task Force on Bidding for Professional Services.
1980 to 1981	Member, Research Committee, Association of Canadian Universities for Northern Studies.
1980 to 1984	Member, Executive, Canadian Geoscience Council. Vice-President (1982); President. (1983)
1981	Member, Organizing Committee, Third International Symposium in Ground Freezing.
1981	Member, Task Force to Establish NRC Cold Regions Facility in Alberta
1981 to 1984	Member, Organizing Committee, 4th International Symposium in Landslides
1983 to 1986	Member, US National Research Council Committee on Ground Failure Hazards
1983 to 1987	Member, Organizing Committee, 6th International Congress on Rock Mechanics
1983	Member, Dean's Review Committee, Dept. of Civil Engineering, University of Toronto
1984	Member, NSERC Task Force on Research Infrastructure
1984 to 1992	Member, Canadian Standards Association Committee, on preparation of code for offshore structures.
1985 to 1986	Member, Organizing Committee, 3rd Canadian Marine Geotechnical Conference
1985 to 1988	Member, Organizing Committee, ASCE Specialty Conference on Hydraulic Fill Structures
1985 to 1989	Member, Executive, International Society for Soil Mechanics and Foundation Engineering
1988	Member, NSERC Supercomputer Funds Allocation Committee
1988	Member, Expert Advisory Committee for International Decade for Natural Disaster Reduction, United Nations
1989 to 1991	President, Canadian Geotechnical Society
1989 to 1991	Vice-President, Engineering Institute of Canada

1989 to 1994	President, International Society for Soil Mechanics and Foundation Engineering
1989 to 1991	Member, RSC/CAE Task Force on Canadian response to IDNDR
1989 to 1993	Advisory Board, The Northern Engineer, University of Alaska
1989 to 1991	Advisory Board, Int. Conf. on Geotechnical Engineering for Coastal Development, Tokyo
1991 to 1992	Member, NATO Science-Collaborative Grants Committee
1992 to 1998	Member, Finance Committee, Royal Society of Canada
1992 to 1997	Member, Fund Raising Committee, Royal Society of Canada
1993 to 2000	Member, Canadian National Committee for International Decade for Natural Disaster Reduction
2000	Member, U.S. National Research Council Committee on Coal Waste Impoundment
2001 to 2004	Member, Killam Prize Selection Committee, Canada Council
2002 to 2004	Member, U.S. National Research Council Committee on National Landslide Hazards Mitigation Strategy
2003 to 2004	Member, ASTech Awards Selection Panel
2003 to date	Chair, Management Committee, Oil Sands Tailings Research Facility
2004 to date	Member, National Research Council Monograph Board
2006 to date	Member, Scientific Advisory Board, Council of Canadian Academies

HONOURS AND AWARDS

1961	British Geotechnical Society Prize
1966	British Geotechnical Society Prize
1971	Walter L. Huber Civil Engineering Research Prize, American Society of Civil Engineers
1974	Gzowski Society Lecture, University of Western Ontario
1975	Fellow, Royal Society of Canada, Academy of Sciences
1977	Canadian Geotechnical Society Prize
1979	Legget Award, Canadian Geotechnical Society
1981	Rankine Lecture, British Geotechnical Society
1981	Boase Lecture, University of Colorado
1981	University of Toronto, Engineering Alumni, Class of '25 Award
1983	University Professor of Civil Engineering, University of Alberta
1983	D.Eng. (h.c.) University of Toronto
1984	University Research Prize, University of Alberta
1984	Centennial Award, Association of Professional Engineers, Geologists and Geophysicists of Alberta
1985	Fellow, Engineering Institute of Canada
1985	Canadian Geotechnical Society Prize
1987	Sir Frederick Haultain Prize in Science, Government of Alberta
1987	Roger J.E. Brown Memorial Award, Canadian Geotechnical Society
1987	Thomas Roy Award, Canadian Geotechnical Society
1988	Fellow, Canadian Academy of Engineering
1988	Distinguished Lecturer, Memorial University of Newfoundland
1988	Distinguished Geotechnical Lecturer, Colorado State University
1989	D.Sc. (h.c.) Queen's University

-
- 1989 6th Manuel Rocha Memorial Lecture, Portuguese Society for Geotechnique
 - 1990 Honorary Research Fellow, Institute of Water Conservancy and Hydroelectric Power Research, Beijing, PRC
 - 1991 Geotechnical Society of Edmonton Award
 - 1991 Alberta Order of Excellence
 - 1992 Foreign Associate, U.S. National Academy of Engineering
 - 1992 27th Karl Terzaghi Lecture, American Society of Civil Engineers
 - 1993 125 Year Commemorative Medal, Government of Canada
 - 1993 Honorary Professor, Central Research Institute of Building and Construction, Ministry of Metallurgical Industry, PRC
 - 1994 Kersten Lecture, University of Minnesota
 - 1994 50th Anniversary Lecture, Hydro-Quebec
 - 1995 Engineering Alumni Medal, University of Toronto
 - 1995 Alberta Science and Technology Foundation Prize for Innovation in Oil Sands Research
 - 1995 3rd Casagrande Lecture
 - 1996 Foreign Member, Royal Academy of Engineering, United Kingdom
 - 1997 Fellow, Canadian Society of Civil Engineers
 - 1998 Nikkon Sekai Nakase Lecture, Tokyo
 - 1999 International Honorary Member, Japanese Geotechnical Society
 - 1999 Foreign Fellow, Indian National Academy of Engineering
 - 2000 R.M. Quigley Award, Canadian Geotechnical Society
 - 2000 The First Lumb Lecture (Hong Kong)
 - 2001 Member, Order of Canada
 - 2001 2001 Killam Prize in Engineering
 - 2001 R.M. Quigley Award, Canadian Geotechnical Society
 - 2002 CAN-AM Civil Engineering Amity Award, American Society of Civil Engineers
 - 2002 The Queen's Golden Jubilee Medal
 - 2003 Sir John Kennedy Medal, Engineering Institute of Canada
 - 2005 Harold R. Peyton Award for Cold Regions Engineering, American Society of Civil Engineers
 - 2006 R.M. Quigley Award, Canadian Geotechnical Society
 - 2006 Varnes Medal, International Consortium for Landslides
 - 2007 D.Sc. (h.c.), University of Alberta
 - 2009 Schuster Medal, Association of Engineering Geologists and Canadian Geotechnical Society
 - 2011 H. Bolton Seed Medal and See Lecture, American Society of Civil Engineers
 - 2011 Fellow, American Society of Civil Engineers
 - 2012 Queen Elizabeth II Diamond Jubilee Medal
 - 2014 Honorary Professor, Zhejiang University, PRC
 - 2015 Honorary Fellow, Canadian Academy of Engineering

PUBLICATIONS

Dr. Morgenstern has authored or co-authored over 300 refereed papers, conference papers and presentations, major reports and book reviews. A listing of these is available upon request.

Douglas VanDine P.Eng./P.Geo.
Geological and Geotechnical Engineer
VanDine Geological Engineering Limited, **Victoria, BC**

EDUCATION

BSc (Eng), Geological Engineering, 1972, Queen's University, Kingston, Ontario, Canada
MSc (Eng), Civil Engineering (Geotechnical), 1975, Queen's University, Kingston, Ontario, Canada

EXPERIENCE

1984-present: VanDine Geological Engineering Limited, Victoria, BC

Mr. VanDine provides specialized geological and geotechnical engineering consulting for civil engineering developments and the forestry industry. His areas of expertise include: landslide and debris flow studies and associated mitigative design work; geological engineering mapping; terrain mapping and route location; geological hazard and risk analyses; mineral aggregate location and evaluation; technical review, forensic engineering, expert witness; and education and training. Mr. VanDine has been a member of numerous federal, provincial and professional committees on engineering and geoscience. He has taught courses associated with geological and geotechnical engineering at University of British Columbia (Vancouver, BC), University of Victoria (Victoria, BC), Camosun College (Victoria, BC), BC Forestry Continuing Studies Network (Vancouver, BC), Institute of Engineering (Kathmandu, Nepal), and University of the West Indies (Kingston, Jamaica). Mr. VanDine has been involved both in developing and carrying out both compliance audits for the BC Forest Practices Board, and General and Technical Professional Practice Reviews for the Association of Engineers and Geoscientists of the Province of British Columbia. He has participated in a number of expert panels and review panels, both in Canada and Hong Kong. In 2010 he was appointed a panel member of the BC Environmental Appeals Board, Forest Appeals Commission and Oil and Gas Appeals Tribunal.

1982-1984 and 1974-1976: Thurber Consultants Ltd, BC and Alberta

Mr. VanDine carried out a wide variety of projects including major reservoir shoreline stability studies of BC Hydro's Peace River developments, engineering terrain assessments of rail lines for CN Railway, and land use planning, aggregate and groundwater studies. He had major input into the Sea to Sky and Coquihalla highways debris flow investigations and mitigative studies for the BC Ministry of Transportation and Infrastructure.

1978-1982: Assistant Professor, Geological Engineering, Queen's University, Ontario

Mr. VanDine taught courses in Engineering Geology, Site Investigation, Airphoto Interpretation, Engineering Terrain Analysis, Urban Geology, and Geology for Engineers. His areas of research included slope stability, aggregates, geotextiles and engineering terrain analysis. During this period Mr., VanDine was a consultant on projects in Ontario and the Maritimes, in the USA, and in Guyana, South America.

1976-1978: Gartner Lee Associates Limited, Ontario

Mr. VanDine conducted a number of mineral aggregate assessments, hydrogeological studies, subdivision planning studies and engineering terrain studies in Ontario and Manitoba. Major

projects included the Northern Ontario Engineering Geology Terrain Studies for the Ontario Geological Survey, and a sand and gravel resources study for 12,000 km² in central Manitoba.

1972-1973: Geological Survey of Canada, BC and NWT

Mr. VanDine was involved in the Granular Resources Inventory Mackenzie Valley project, permafrost degradation studies in the same valley, and a study of natural and human-induced landslides along the Thompson and Fraser rivers, BC.

1971: Terra Scan Limited, Ontario

This work involved drill inspection, instrumentation, construction supervision and laboratory testing for a variety of geological and geotechnical engineering studies.

MEMBERSHIPS

Professional Engineers and Geoscientists of British Columbia (P.Eng. and P.Geo.)
Professional Engineers of Alberta and Ontario (P.Eng. resigned member in good standing)
Professional Engineers of Nova Scotia (P.Eng. resigned licensee in good standing)
Canadian Geotechnical Society (CGS); Engineering Geology Division (EGD); International Association of Engineering Geology (IAEG)

APPOINTMENTS

President (2015-2016), Canadian Geotechnical Society
Panel Member, BC Environmental Appeals Board, Forest Appeals Commission and Oil and Gas Appeals Tribunal (2010-present)
Trustee, Canadian Foundation for Geotechnique (1999-2013); Vice President and National Fund Raising Chair (2005-2008); President (2008-2013)
Member, Association of Professional Engineers and Geoscientists of British Columbia, President's Awards Committee (2008-2013); Chair (2010-2013)
Scientific Editor and Member of Advisory Panel, Canadian Technical Guidelines and Best Practices related to Landslides: a national initiative for loss reduction, Geological Survey of Canada, (2010-2013)
Member, Association of Professional Engineers and Geoscientists of British Columbia, Task Force on Geotechnical Engineering Definition and Competencies (2009-present)
Series Editor, The Geology of the Federal, Provincial and Territorial Parliament Building of Canada, *Geoscience Canada* (2001-2009)
Member, Advisory Committee, International Debris-Flow Hazards and Mitigation Society (2000-2009)
Director, Institute of Forest Engineering of British Columbia (1996-1997)
Member, National Mapping Program Coordinating Committee, Geological Survey of Canada (1995-2001)
Member, Joint Practice Board (JPB), Association of Professional Engineers and Geoscientists of British Columbia/ Association of British Columbia Professional Foresters (1995-1998); Chair (1995-1996)
Executive, Division of Engineers and Geoscientists in the Forest Sector (DEGIFS), Association of Professional Engineers and Geoscientists of British Columbia (1995-1998)
Member, Canadian Geoscience Council Committee on the Future of Geosciences in Canada (1994-1995)

Member, Earth Science Task Force of the British Columbia Resources Inventory Committee (1993-1998)
Member, Advisory Committee, British Columbia Geological Survey Branch, Surficial Geology Unit (1989-1995)
Associate Editor, Canadian Geotechnical Journal (1988-1990)
Member and Treasurer, Canadian Geoscience Council (now known as the Canadian Foundation for Earth Sciences) (1984-1988 and 1990)
Chairman, Engineering Geology Division, Canadian Geotechnical Society (1984-1986)

AWARDS AND HONOURS

Geoscientists Canada (formerly Canadian Council of Professional Geoscientists), Fellow (FGC 2013)
Engineers Canada (formerly Canadian Council of Professional Engineers), Fellow (FEC 2009)
Engineering Institute of Canada, Fellow (FEIC 2006)
Association of Professional Engineers and Geoscientists of British Columbia, CJ Westerman Award (APEGBC's premier award for professional geoscience) (2005)
Forest Engineering Award of Excellence, Association of Professional Engineers and Geoscientists of British Columbia and Association of British Columbia Professional Foresters (2003)
Association of Professional Engineers and Geoscientists of British Columbia, Professional Service Award (1998)
Canadian Geotechnical Society, Engineering Geology Division, Thomas Roy Award (1998)
8th Canadian Geotechnical Colloquium Speaker of the Canadian Geotechnical Society (1984)
Engineering Society Teaching Award, Queen's University (1981)

PUBLICATIONS

Mr. VanDine has authored or co-authored over 75 refereed papers, conference papers and presentations, major reports and book reviews. A listing of these is available upon request.