PROFESSIONAL PRACTICE GUIDELINES

NATURAL HAZARDS

LANDSLIDE ASSESSMENTS IN BRITISH COLUMBIA

VERSION 4.1
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ENGINEERS & GEOSCIENTISTS
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PREFACE

These *Professional Practice Guidelines – Landslide Assessments in British Columbia* were developed by Engineers and Geoscientists British Columbia to guide professional practice related to Landslide Assessments.

These guidelines were first published in 2006 to address the need for a common understanding between authorities having jurisdiction and Qualified Professionals as to the nature and requirements of legislated Landslide Assessments. They were updated in 2008 and 2010.

This revision provides additional clarity on current methods and techniques used to perform Landslide Assessments. Importantly, these guidelines expand the content to encompass the requirements of Landslide Assessments for non-legislated and existing developments, as well as those of legislated and proposed Residential Developments addressed in the previous versions of these guidelines. Legislated Landslide Assessments are explicitly required by provincial or national enactments. Non-legislated Landslide Assessments may be performed based on local or regional government development and permitting policies, or may be initiated at the request of a property owner, stakeholder, or rightsholder.

As well, since the last revision in 2010, the demands on regulators and practitioners have increased and evolved substantially. The nature of the work has changed due to increasing development pressure, and with advances in science and methodology. Concurrently, involved parties are transitioning to adaptive management in a changing climate, and coping with rapid technological change in the digital era. This update is intended to respond to these advances.

These guidelines describe expectations and obligations of professional practice related to the specific professional activity of Landslide Assessments to be followed at the time they were prepared. However, this is a living document that is to be revised and updated as required in the future, to reflect the developing state of practice.

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ABBREVIATIONS AND ACRONYMS

ABBREVIATION	TERM
AEP	annual exceedance probability
ALARP	as low as reasonably practicable
BC	British Columbia
BC MOTI	British Columbia Ministry of Transportation and Infrastructure
BCBC	*British Columbia Building Code*
CAD	computer-aided design
CBA	cost-benefit analysis
CCCMA	Canadian Centre for Climate Modelling and Analysis
CMIP	Coupled Model Intercomparison Project
DHC	displacement hazard curve
F-M	frequency-magnitude
FS	Factor(s) of Safety
g	acceleration due to gravity
GCMs	general circulation models
GIS	geographic information system
GPS	global positioning system
GSC	Geological Survey of Canada
IFF	impact force frequency
InSAR	interferometric synthetic aperture radar
IPCC	Intergovernmental Panel on Climate Change
LiDAR	light detection and ranging
MCA	multi-criteria analysis
NBC	*National Building Code of Canada*
PCIC	Pacific Climate Impacts Consortium

ABBREVIATION	TERM
PDI	annual probability of death to an individual
PEER	Pacific Earthquake Engineering Research Center
PGA	peak ground acceleration
PGV	peak ground velocity
QEP	qualified environmental professional
QP	Qualified Professional
QRA	quantitative risk assessment
SfM	structure from motion
TFSSS	Task Force on Seismic Slope Stability
s	second(s)
UHS	uniform hazard spectra
WCRP	World Climate Research Programme

DEFINED TERMS

The following definitions are specific to these guidelines. These words and terms are capitalized throughout the document.

TERM	DEFINITION
Act	*Professional Governance Act* [SBC 2018], Chapter 47.
Agreement	A written contract or terms of engagement between the Client and the Qualified Professional, or their company, for conducting a Landslide Assessment.
Approving Authority	A local or provincial government with the authority to authorize a Proposed Development. NOTE: In other guidelines or contexts, this role may be referred to as the Authority Having Jurisdiction.
Approving Officer	An official who is appointed under the *Land Title Act* (Section 77) and acts independently to (1) ensure that subdivisions comply with provincial acts and regulations and local bylaws, and (2) protect the public interest. There are five types of Approving Officers in British Columbia: 1. Municipal Approving Officers – Appointed by: municipal councils/boards – Jurisdiction: subdivision approvals within municipal boundaries 2. Regional District and Islands Trust Approving Officers – Appointed by: Regional District boards or the Islands Trust council – Jurisdiction: subdivision approvals within the boundaries of those Local Governments that have assumed the rural subdivision Approving Authority* 3. Provincial Approving Officers – Appointed by: provincial cabinet – Jurisdiction: subdivision approvals outside municipal boundaries and within those Regional Districts and the Islands Trust boundaries that have not assumed the rural subdivision Approving Authority* 4. Treaty First Nation Approving Officers – Appointed by: treaty First Nation government – Jurisdiction: subdivision approvals within the treaty First Nation lands 5. Nisga'a Lands Approving Officers – Appointed by: Nisga'a Lisims Government – Jurisdiction: subdivision approvals within Nisga'a Lands, including Nisga'a village lands NOTE: * No Regional District, nor the Islands Trust, has assumed responsibility for rural subdivision approvals; therefore, that authority is still held by the BC Ministry of Transportation and Infrastructure.

TERM	DEFINITION
BC Ministry of Transportation and Infrastructure (BC MOTI)	The provincial ministry responsible for rural subdivision approvals outside municipal boundaries and within those Regional Districts and the Islands Trust boundaries that have not assumed the rural subdivision Approving Authority. Under the *Land Title Act* (Sections 75(1) and 80) the BC MOTI must approve subdivision plans in Local Government jurisdictions where: • a subdivision will be located adjacent to a controlled access highway in municipal or rural areas; • a highway will be a component of Regional District or Islands Trust approved subdivisions; and • relief from access to water is being granted pursuant to the *Land Title Act* in rural or incorporated areas.
Building Inspector	An individual appointed by a Local Government to administer its building bylaw within the context of the *BC Building Code* or, in the case of the City of Vancouver, the Vancouver Building By-law. The Islands Trust does not have Building Inspectors.
Bylaws	The Bylaws of Engineers and Geoscientists BC made under the *Act*.
Client	An individual or company who engages a Qualified Professional to conduct a Landslide Assessment.
Consequence	A result or effect on human well-being, property, or the environment due to a Landslide occurring.
Construction	Either new Construction of a building or structure, or the structural alteration of or addition to an existing building or structure. Construction does not include the repair of an existing building or structure.
Covenant	A registered agreement, established by the *Land Title Act* (Section 219), between a Landowner and the local or provincial government that sets out certain conditions for a specific property with regards to building use, building location, land use, property subdivision, and/or property sale.
Development Consultant	An individual or company retained by a Landowner to plan and oversee development of a parcel of land or to look after the affairs of the land. This individual or company may be an architect, a BC land surveyor, a civil (land development) engineer, a land use planner, a realtor, or a family member.
Element(s) at Risk	Things of social, environmental, and economic value, including human well-being and property, that may be affected by a Landslide.
Engineering/Geoscience Professional(s)	Professional engineers, professional geoscientists, professional licensees engineering, professional licensees geoscience, and any other individuals registered or licensed by Engineers and Geoscientists BC as a "professional registrant" as defined in Part 1 of the Bylaws.
Engineers and Geoscientists BC	The Association of Professional Engineers and Geoscientists of the Province of British Columbia, also operating as Engineers and Geoscientists BC.
Environmental Geoscience	The application of geology and related earth sciences to obtain information on, and an understanding of, geological materials, processes, and structures as needed for engineering and environmental investigation, analysis, and design.

TERM	DEFINITION
Factor(s) of Safety (FS)	As related to slope stability, the ratio of the shear strength of the soil or rock that comprise the slope divided by the shear stresses within the slope. The most common method of estimating Factor of Safety is using a limit equilibrium analysis method. When seismic or other dynamic loadings are not considered, this is referred to as a static limit equilibrium limit analysis. When seismic or other dynamic loadings are considered, this is referred to as a pseudo-static limit equilibrium analysis.
Geological Engineering	The application of a combination of geology, engineering, and related disciplines to the investigation, analysis, and design involving rock, soil, water, and mineral resources for engineering and environmental projects.
Geotechnical Engineering	The application of soil mechanics, rock mechanics, engineering geology, and related disciplines to the investigation, analysis, and design involving rock, soil, and water for engineering and environmental projects.
Ground Motion(s)	A general term for all seismic-related motions of the ground, including ground acceleration, slope displacement, and stress and strain.
Islands Trust	The autonomous Local Government, established by the *Islands Trust Act*, with land use planning and regulatory authority similar to those of a Regional District but without the role of building inspection. The Islands Trust has broad authority for coordinating work with other agencies, organizations, and groups. The Islands Trust area covers the islands and waters between the British Columbia mainland and southern Vancouver Island, including Howe Sound and as far north as Comox. First Nations Reserves are not included in the Islands Trust area.
Landowner	An individual or company identified as the owner on the title of the land registered in a Land Title Office.
Landslide(s)	A movement of rock, debris, or earth down a slope. Landslides can be a result of a natural sequence of events and/or human activities. The *Land Title Act* (Section 86) refers to the following natural hazards: "flooding, [soil] erosion, land slip and [snow] avalanche." The *Local Government Act* (Section 920) refers to: "flooding, mud flows, torrents of debris, [soil] erosion, land slip, rock falls, subsidence, tsunami, [snow] avalanches or wildfire." The *Community Charter* (Section 56) refers to: "flooding, mud flows, debris flows, debris torrents, [soil] erosion, land slip, rock falls, subsidence and [snow] avalanche." These guidelines address only Landslides referred to as "land slips, debris flows, debris torrents, mud flows, and rock falls," as identified in the above lists. They do not address the other natural hazards listed in those documents, except as they relate to Landslides. For the purpose of these guidelines, Landslides include the following: • rockfalls, rock slumps, rockslides, rock avalanches, rock creep; • debris falls, debris slides, debris flows, debris floods; • earth falls, earth slumps, earth slides, earth flows, earth creep; and • flow slides. Debris flows and debris floods have some characteristics of both Landslides and floods. For debris flows, this document supersedes the *Professional Practice Guidelines – Legislated Flood Assessments in a Changing Climate in BC* (Engineers and Geoscientists BC 2018a).

TERM	DEFINITION
Landslide Assessment	(noun) A set of work, performed by a Qualified Professional and culminating in a report, to determine the Landslide Hazards and/or Landslide Risks associated with the selected area of study. (verb) The act of gathering information and performing analysis of geophysical conditions in a study area in order to determine Landslide Hazard or Landslide Risk.
Landslide Assessment Assurance Statement	The assurance statement that is submitted with the Landslide Assessment Report to an Approving Authority. (See Appendix D).
Landslide Assessment Report	A report written by a Qualified Professional to outline the development proposal, hazard context, methods, and results of the Landslide Assessment work that was completed. It may be a Landslide Hazard assessment, a Landslide Risk assessment, or some combination of those.
Landslide Hazard	A source of potential harm, or a situation with a potential for causing harm, including damage to health, property, the environment, other things of value, or some combination of those, resulting from a Landslide.
Landslide Risk	An estimate of Landslide Hazard and potential Consequences to an Element at Risk.
Level(s) of Landslide Safety	Level of safety from the effects of Landslides, including levels of acceptable Landslide Hazard and Landslide Risk.
Local Government	Municipalities, Regional Districts, First Nations, and the Islands Trust.
Municipality	A corporation into which the residents of an area are incorporated under the *Local Government Act* or another act, or the geographic area of the municipal corporation.
Official Community Plan	A statement of objectives and policies to guide decisions on planning and land use management within the area covered by the plan, respecting the purposes of the Local Government (*Local Government Act*, Part 26, Division 2).
Qualified Professional	An Engineering/Geoscience Professional with the appropriate level of education, training, and experience to conduct Landslide Assessments as described in these guidelines. A Qualified Professional may practice professional engineering and/or professional geoscience in the profession(s) in which they are registered.
Regional District	A district incorporated under the *Local Government Act*, or the geographic area of the district, with authority to enact subdivision servicing and zoning bylaws.
Registrant	Means the same as defined in Schedule 1, section 5 of the *Professional Governance Act*.
Residential Development	As defined by various pieces of provincial legislation, either: • the subdivision of property; • the new Construction of a building or structure; or • the structural alteration of, or addition to, an existing building or structure.
Site-Specific Response Analysis	The process of calculating the free-field response of a soil deposit to earthquake shaking. Wave-propagation from reference firm ground through the overlying soil column is solved using one-dimensional methods.

VERSION HISTORY

VERSION NUMBER	PUBLISHED DATE	DESCRIPTION OF CHANGES
4.1	March 1, 2023	Minor revision to correct equations in Appendix E3.3 and to add reviewer.
4.0	September 29, 2022	Revised to provide additional clarity on current methods and techniques used to perform Landslide Assessments; to expand the content to encompass Landslide Assessments for non-legislated and existing developments, as well as those for legislated and proposed Residential Developments; and to align with the requirements of the *Professional Governance Act*.
3.0	May 2010	Revised to align with amendments to the *BC Building Code* 2006 per ministerial orders M296 and M297.
2.0	September 2008	Revised to align with the *BC Building Code 2006*.
1.0	March 2006	Initial version.

1.0 INTRODUCTION

Engineers and Geoscientists British Columbia is the regulatory and licensing body for the engineering and geoscience professions in British Columbia (BC). To protect the public, Engineers and Geoscientists BC establishes, monitors, and enforces standards for the qualification and practice of its Registrants.

Engineers and Geoscientists BC provides various practice resources to its Registrants to assist them in meeting their professional and ethical obligations under the *Professional Governance Act* (the *Act*) and Engineers and Geoscientists BC Bylaws (Bylaws). Those practice resources include professional practice guidelines, which are produced under the authority of Section 7.3.1 of the Bylaws and are aligned with the Code of Ethics Principle 4.

Each professional practice guideline describes expectations and obligations of professional practice that all Engineering/Geoscience Professionals are expected to have regard for in relation to specific professional activities. Engineers and Geoscientists BC publishes professional practice guidelines on specific professional activities where additional guidance is deemed necessary. Professional practice guidelines are written by subject matter experts and reviewed by stakeholders before publication.

Having regard for professional practice guidelines means that Engineering/Geoscience Professionals must follow established and documented procedures to stay informed of, be knowledgeable about, and meet the intent of any professional practice guidelines related to their area(s) of practice. By carefully considering the objectives and intent of a professional practice guideline, an Engineering/Geoscience Professional can then use their professional judgment when applying the guidance to a specific situation. Any deviation from the guidelines must be documented and a rationale provided. Where the guidelines refer to professional obligations specified under the *Act*, the Bylaws, and other regulations/legislation, Engineering/Geoscience Professionals must understand that such obligations are mandatory.

These *Professional Practice Guidelines – Landslide Assessments in British Columbia* provide guidance on professional practice for Engineering/Geoscience Professionals who are engaged in slope stability analyses and/or Landslide Hazard and Landslide Risk assessments. The assessment and the associated report are usually one early step in the development process, and are prepared to characterize the Landslide Hazard or Landslide Risk affecting a proposed use and, if required, to present conceptual mitigation measures tobe designed during later stages of the development process.

These guidelines were first published in 2006, and they were revised in 2008 and 2010 to incorporate changes to the *BC Building Code*. Since the last revision in 2010, the demands on regulators and practitioners have increased and evolved substantially. The nature of the work has changed due to increasing development pressure, and with advances in science and methodology. Concurrently, involved parties are transitioning to adaptive management in a changing climate, and coping with rapid technological change in the digital era. This update is intended to respond to these advances.

INTRODUCTION TO THE 2022 UPDATE

The intent of this update to these guidelines is to provide current guidance for preparing high-quality Landslide Assessments that present interpretations of Landslide Hazard or slope safety that adequately reflect actual circumstances and are based on current practice in Landslide Assessment.

The main reasons for this update to these guidelines are as follows:

1. To expand the content and focus to address both legislated[1] and non-legislated Landslide Assessments for existing and proposed residential, industrial, public, and commercial developments, to ensure Landslide Assessments for such infrastructure are carried out to the same expectations as proposed legislated developments that were the focus of previous versions. Note that where a sector has its own specific practice guidelines, such as the forestry sector, these guidelines may augment but do not supersede those guidelines.
2. To reflect changes in expectations and obligations of professional practice, including advances in Landslide Assessments and mapping, improvements in seismic slope stability assessments, technological advances, and improved understanding of the effects of climate change.
3. To include practices that incorporate recent advances in professional practice.
4. To update the content to align with the requirements of the *Act* and related regulations.

The province of BC still does not have provincially defined Levels of Landslide Safety, and as such these guidelines continue to promote an approach that relies upon levels adopted in other jurisdictions and by Local Governments to guide Qualified Professionals (QPs). While safety has often been evaluated assuming "life-safety," risk analysis and management in BC has evolved: direct damages, other externalities such as business losses, historical/cultural impacts, and human well-being impacts all contribute to risk and may need to be considered. This is especially the case when considering existing development and strategies to mitigate risk, such as monitoring and early warning.

1.1 PURPOSE OF THESE GUIDELINES

This document provides guidance on professional practice to QPs who are engaged in slope stability analyses and/or Landslide Hazard and Landslide Risk assessments. The purpose of these guidelines is to provide a common approach for carrying out a range of professional activities related to this work.

Following are the specific objectives of these guidelines:

1. Describe expectations and obligations of professional practice that Engineering/Geoscience Professionals are expected to have regard for in relation to the specific professional activity outlined in these guidelines by:
   - specifying tasks and/or services that Engineering/Geoscience Professionals should complete;
   - referring to professional obligations under the *Act*, the Bylaws, and other regulations/legislation, including the primary obligation to protect the safety, health, and welfare of the public and the environment; and
   - describing the established norms of practice in this area.
2. Describe the roles and responsibilities of the various participants/stakeholders involved in these professional activities. The document should assist in delineating the roles and responsibilities of the various participants/stakeholders, which may include the QP, owners/Clients, Approving Authority, and contractors.

[1] Legislated Landslide Assessments are explicitly required by provincial or national enactments, including those listed in Appendix A: Legislative Framework. Non-legislated Landslide Assessments may be performed based on local or regional government development and permitting policies, or may be initiated at the request of a property owner, stakeholder, or rightsholder.

3. Define the skill sets that are consistent with the training and experience required to carry out these professional activities.
4. Provide guidance on the use of assurance documents, so the appropriate considerations have been addressed (both regulatory and technical) for the specific professional activities that were carried out.
5. Provide guidance on how to meet the quality management requirements under the *Act* and the Bylaws when carrying out the professional activities identified in these professional practice guidelines.

1.2 ROLE OF ENGINEERS AND GEOSCIENTISTS BC

These guidelines form part of Engineers and Geoscientists BC's ongoing commitment to maintaining the quality of professional services that Engineering/Geoscience Professionals, including QPs as defined in these guidelines, provide to their clients and the public.

Engineers and Geoscientists BC has the statutory duty to serve and protect the public interest as it relates to the practice of professional engineering and professional geoscience, including regulating the conduct of Engineering/Geoscience Professionals. Engineers and Geoscientists BC is responsible for establishing, monitoring, and enforcing the standards of practice, conduct, and competence for Engineering/Geoscience Professionals. One way that Engineers and Geoscientists BC exercises these responsibilities is by publishing and enforcing the use of professional practice guidelines, as per Section 7.3.1 of the Bylaws.

Guidelines are meant to assist Engineering/Geoscience Professionals in meeting their professional obligations. As such, Engineering/Geoscience Professionals are required to be knowledgeable of, competent in, and meet the intent of professional practice guidelines that are relevant to their area(s) of practice.

The writing, review, and publishing process for professional practice guidelines at Engineers and Geoscientists BC is comprehensive. These guidelines were prepared by subject matter experts and reviewed at various stages by formal and informal review groups, and the final draft underwent a thorough consultation process with various advisory groups and divisions of Engineers and Geoscientists BC. These guidelines were then approved by Council and, prior to publication, underwent final editorial and legal reviews.

Engineers and Geoscientists BC supports the principle that appropriate financial, professional, and technical resources should be provided (i.e., by the client and/or the employer) to support Engineering/Geoscience Professionals, including QPs as defined in these guidelines, who are responsible for carrying out professional activities, so they can comply with the professional practice expectations and obligations provided in these guidelines. These guidelines may be used to inform the level of service and terms of reference of an Agreement between an Engineering/Geoscience Professional and a client. However, regardless of any terms in an Agreement, Engineering/Geoscience Professionals remain responsible for compliance with all professional practice guidelines.

1.3 INTRODUCTION OF TERMS

The requirements of Landslide Assessments for non-legislated and existing developments, as well as those of legislated and proposed Residential Developments, are included in this revision of these guidelines.

- **Legislated Landslide Assessments** are explicitly required by provincial or national enactments, including those listed in Appendix A: Legislative Framework.
- **Non-legislated Landslide Assessments** may be performed based on local or regional government development and permitting policies, or may be initiated at the request of a property owner, stakeholder, or rightsholder.

See the Defined Terms section at the front of the document for a full list of definitions specific to these guidelines.

1.4 SCOPE AND APPLICABILITY OF THESE GUIDELINES

These guidelines provide guidance on professional practice for QPs who carry out Landslide Assessments. These guidelines are not intended to provide technical or systematic instructions for how to carry out these activities; rather, these guidelines outline considerations to be aware of when carrying out these activities. QPs must exercise professional judgment when providing professional services; as such, application of these guidelines will vary depending on the circumstances.

An QP's decision not to follow one or more aspects of these guidelines does not necessarily represent a failure to meet professional obligations. For information on how to appropriately depart from the practice guidance within these guidelines, refer to the *Quality Management Guides – Guide to the Standard for the Use of Professional Practice Guidelines* (Engineers and Geoscientists BC 2021a), Section 3.4.2. The rationale for not following aspects of these guidelines for a Landslide Assessment should be justified in the Landslide Assessment Report.

This document provides guidance on professional practice to QPs who carry out Landslide Assessments for existing and/or proposed residential and/or industrial/commercial/public infrastructure developments. This may include hydroelectric facilities, public recreation sites, municipal or mine waste dumps and tailings reservoirs in proximity to downstream developments, wave runup from Landslides into lakes and reservoirs, or various other hazard cascades. The reason for expanding these guidelines to capture a wider array of development types is that when the basic framework of Landslide Assessment applies, it should be applied consistently, and no development should be exempt, unless good reason is provided.

These guidelines are not intended to apply directly to slope stability analysis in support of natural resource industry operations, particularly when those operations are covered by existing guidelines such as those noted below. However, where such operations impact other residential and/or industrial/commercial/public infrastructure development areas, these guidelines apply.

These guidelines are not intended to apply directly to risk assessments for linear infrastructure, such as highways, railways, pipelines, and utilities transmission.

In the case of emergency Landslide Assessments, due to time and budget limitations, the QP may not be able to apply a level of effort comparable to a predictive hazard or risk assessment. In those cases, the agency requesting the emergency Landslide Assessment will need to define the scope based on the current needs (for example analyses to support decisions on issuing, expanding, or cancelling evacuations), and the QP should confirm that scope in the outputs of their work so the limitations are clear to the users.

Some analytical methods differ in that the vulnerabilities and associated risks vary from those that are specific to legislated Residential Developments. If a Landslide Assessment is being carried out for other developments, the QP needs to be aware of any specific guidance documents, regulations, and acts that may govern that development, as the legislated approval process may not apply. The QP is encouraged to use these guidelines as a starting point for the assessment for other types of developments.

This document provides guidance for the QP on how to relate the results of the analysis to a Level of Landslide Safety for situations where Levels of Landslide Safety have been adopted, or where a level of safety is compared to risk tolerance standards developed by other jurisdictions in BC or elsewhere. It also provides some guidance on how the findings of a Landslide Assessment can be translated into risk-reduction measures.

Although these guidelines are intended for QPs, they may be used to assist other parties, such as

Landowners, Development Consultants, land use planners, Approving Officers, Building Inspectors, Municipalities, Regional Districts, the Islands Trust, the provincial government, and the general public, who frequently rely on Landslide Assessments.

Guidance in this document may also overlap with that of several other professional practice guidelines that cover areas of practice specialization related to the impacts of proposed developments on slope stability, such as the following:

- *Professional Practice Guidelines – Professional Services in the Forest Sector - Terrain Stability Assessments* (Engineers and Geoscientists BC 2010)
- *Professional Practice Guidelines – Geotechnical Engineering Services for Building Projects* (Engineers and Geoscientists BC 2021b)
- *Professional Practice Guidelines – Performance-Based Seismic Design of Bridges in BC* (Engineers and Geoscientists BC 2018b)
- *Professional Practice Guidelines – Developing Climate Change–Resilient Designs for Highway Infrastructure in British Columbia* (Engineers and Geoscientists BC 2020a)
- *Professional Practice Guidelines – Legislated Dam Safety Reviews in BC* (Engineers and Geoscientists BC 2016a)
- *Professional Practice Guidelines – Site Characterization for Dam Foundations in BC* (Engineers and Geoscientists BC 2016b)
- *Housing Foundations and Geotechnical Challenges – Best Practices for Residential Builders In British Columbia* (BC Housing 2015)

In particular, the *Professional Practice Guidelines – Legislated Flood Assessments in a Changing Climate* (Engineers and Geoscientists BC 2018a) consider hydrologic floods but also indicate that consideration must be given to debris floods and debris flows. While debris floods are considered fluvial, debris flows are generally considered a Landslide process; therefore, the guidance on debris flows provided in these guidelines supersedes that in the flood assessment guidelines.

Note, however, that these guidelines do not address other potential natural hazards such as flooding, soil erosion (except from where it triggers a Landslide), subsidence, volcanic eruptions (unless associated with land sliding), or snow avalanches. If a QP identifies other potential hazards during a Landslide Assessment, they should notify the Client and the Landowner (in situations where the Client is not the Landowner) who may then issue a study specific to the newly identified problem or add it as a change order to an existing Landslide Hazard assessment, if the QP or the QP's firm is qualified to address the newly identified hazard.

These guidelines exclude erosive but non-Landslide type processes such as piping, gullying, karst development, and soil structure collapse. Currently, there are no professional practice guidelines that cover these hazards. Practitioners should always be alert to all possible processes affecting a site and notify the Client as to any required additional scope.

The following pieces of provincial legislation related to Residential Development may require the involvement of a QP, as defined in these guidelines, but do not include an explicit requirement within the statue to involve a QP:

- A Local Government developing an Official Community Plan, designating a development permit area, or preparing a bylaw, including flood plain[2] and zoning bylaws and subdivision approval, under the *Local Government Act*
- A Local Government issuing a tree cutting permit, under the *Local Government Act*
- The Ministry of Land, Water, and Resource Stewardship disposition of Crown land, under the *Land Act*
- A riparian assessment conducted according to the *Riparian Areas Protection Regulation*, under the *Riparian Areas Protection Act*

[2] Flood plains as related to Landslides.

1.5 OVERVIEW OF THE STRUCTURE OF THESE GUIDELINES

These guidelines contain the following sections:

- Section 1 introduces and identifies the need and purpose of these guidelines, clarifies the role of Engineers and Geoscientists BC, introduces defined and other terms, and sets out the applicability of these guidelines.
- Section 2 lists common forms of project organization and lists the responsibilities that are ordinarily to be carried by the Client, the QP, the Approving Authorities, and reviewers.
- Section 3 is the backbone of these guidelines and provides the QP as well as Approving Officers, as appropriate, with guidance on the requirements for hazard and risk assessments. This section is supported by various appendices, notably Appendix B: Landslide Assessment – Determining the Level of Effort, Appendix E: Methods of Seismic Analysis of Soil Slopes, and Appendix F: Evolving Practice.
- Section 4 provides guidance on quality management in professional practice, including various review requirements.
- Section 5 summarizes the requirements for professional registration, and for education, training, and experience.
- Section 6 provides references that correspond to in-text citations, and lists other related documents of interest.

These guidelines also include a set of appendices that include the following information:

- Appendix A: Legislative Framework contains applicable laws to be aware of when conducting Landslide Assessments.
- Appendix B: Landslide Assessment – Determining the Level of Effort includes tables that guide the QPs as to the appropriate level of effort (equivalent in most cases to work scope) for a range of assignments, from a scoping study to a very detailed quantitative risk assessment for a large development threatened by a potentially lethal Landslide.
- Appendix C: Review of Levels of Landslide Safety includes a brief review of levels of Landslide life loss safety applicable in Canada and BC, and instituted by Local Governments.
- Appendix D: Landslide Assessment Assurance Statement includes the required assurance statement to be provided by the QP.
- Appendix E: Methods of Seismic Analysis of Soil Slopes contains an update of existing methods in the seismic analysis of soils slopes.
- Appendix F: Evolving Practice includes current techniques and applications for Landslide Assessments, which should be considered by the QP depending on the specific scope of work; for example, climate change considerations in Landslide Assessment and new techniques of Landslide Hazard mapping for rapid Landslides that may result in building destruction or loss of life.
- Appendix G: Strategies for Uncertainty Reduction provides methods for addressing and communicating knowledge uncertainty and natural uncertainty, key issues in any Landslide Assessment.
- Appendix H: Methods for Landslide Risk Reduction discusses various ways for how Landslide Risk can be reduced, including non-structural techniques.
- Appendix I: Authors and Reviewers acknowledges the contributors to this version of these guidelines.

1.6 ACKNOWLEDGEMENTS

This document was reviewed by a group of technical experts, as well as by various advisory groups and divisions of Engineers and Geoscientists BC. Authorship and review of these guidelines does not necessarily indicate the individuals and/or their employers endorse everything in these guidelines.

Specifically, this document was written by senior practitioners familiar with large-scale hazard and risk assessments (M. Jakob, P.Geo.), small and medium-scale assessments mostly for individuals and/or developers (P. Friele, MSc., P.Geo.), and seismic slope stability assessments (J. Wetherill, P.Eng.), and by D. Rankin, P.Eng. from Engineers and Geoscientists BC. These guidelines were then reviewed by a group of technical experts in consulting and academia, as well as by planners and engineers in Local Governments.

Engineers and Geoscientists BC thanks the authors and reviewers of the original documents, as well as the authors and reviewers of this revision, for their time and effort in sharing their knowledge and experience. A full list of authors and reviewers of this revision is provided in Appendix I: Authors and Reviewers.

Engineers and Geoscientists BC also thanks Christy Costello, Editorial Coordinator, for editorial review and design support, which enhanced the clarity, consistency, and presentation of these guidelines.

2.0 ROLES AND RESPONSIBILITIES

2.1 COMMON PROJECT CONSIDERATIONS

Landslide Assessments for subdivision approvals, development permits, building permits, and exemptions are legislated by various acts (Appendix A: Legislative Framework) and initiated by the Local Government or the provincial government that is requesting the Landowner or Development Consultant to retain a Qualified Professional (QP) to carry out a Landslide Assessment and prepare a report.

The Landowner or Development Consultant is the Client that establishes an Agreement for professional services with the QP. The Landowner or Development Consultant then forwards the report to the requesting government body, usually an Approving Authority, for review and either acceptance or rejection of the conclusions and recommendations contained in the report.

Outside of the legislated framework, a purchaser may request an assessment to determine constraints and development feasibility of a particular land parcel, or, at the Local Government or Regional District scale, a QP may be hired by government to produce hazard/risk zoning maps to aid the development approvals process or to provide independent advice. In the case of regional-scale planning initiatives, entire Regional Districts or large watersheds may come under analysis. In those cases, the Client is typically the Regional District or some other entity managing the funds (i.e., Fraser Basin Council).

Note that in these guidelines, in the absence of Local Government policies, and consistent with approaches described in the Canadian Avalanche Association guidelines *Technical Aspects of Snow Avalanche Risk Management* (CAA 2016) and the *Professional Practice Guidelines – Legislated Flood Assessments in a Changing Climate* (Engineers and Geoscientists BC 2018a), guidance is provided for levels of effort, and appropriate typical partial risk values to use in quantitative risk analysis for various levels of risk exposure (Appendix B: Landslide Assessment – Determining the Level of Effort). The QP should be aware that the Landslide Assessment Report will ultimately be referenced by an Approving Authority or formally reviewed by an external reviewer.

The Client should be aware that the findings of the QP could result in modifications to the development plan as a result of siting constraints or protective works to reduce risk. In the case of Residential Development, the Approving Authority may require Covenants, or the development may not be approved. Therefore, it is useful for the Landslide Assessment to be carried out early in the development planning process. In cases with existing development, the findings from the report can identify properties where risks are only tolerable or unacceptable, and can be used to examine risk management strategies that serve to upgrade those sites or protect the entire development. In cases where a development proposal incrementally increases the population density, and hence risk, the QP may be asked to show that the densification does not increase societal (group) risk above locally adopted thresholds, where such thresholds exist.

When QPs are assessing Landslide Hazards where multiple fatalities could result from a single event, Engineers and Geoscientists BC supports evaluation of societal risk, especially in cases where gradual densification could lead to a substantial increase in societal risk. Where no such policies exist, the QP may wish to inform the Approving Authority of concerns regarding the development area and indicate that societal risk be estimated. This will allow for better risk-informed development policies.

The QP should ensure that the role of the QP in relation to the Client and the Approving Authority is clearly defined. An example would be the different skill sets required for assessment and design. QPs are required to clearly understand whether they have any personal limitations in training and experience; if so, they must not practice outside of those limits (unless directly supervised by another QP with appropriate training and experience) and must convey these limitations to the Client and Approving Authority.

It is possible that a Client may not have been previously involved in a development, or may not have previously engaged a QP. In such situations, the QP should review with the Client the typical responsibilities listed in Section 2.2 below, to assist in establishing an appropriate Agreement for professional services (Code of Ethics Principle 5).

2.2 RESPONSIBILITIES

Sections 2.2.1, 2.2.2, and 2.2.3 describe some of the typical responsibilities of a Client, QP, and Approving Authority, respectively. Section 2.2.4 describes some of the typical responsibilities of a QP when asked by an Approving Authority or Client to provide a peer review of a Landslide Assessment Report prepared by another QP. Section 2.2.5 describes the role of the Independent Reviewer, when an independent review is required for high-risk activities such as Landslide Assessments.

2.2.1 CLIENT

The Client is typically the Landowner or the Development Consultant. Occasionally, the Client is the Local Government, the provincial government, or a government agency where the study overlaps with their interests or land ownership.

Before undertaking a Landslide Assessment, the Client should be knowledgeable about and provide the QP with the following information:

- Processes and procedures of subdivision approvals, development permits, building permits, and flood plain bylaw variance or exemption, as applicable[3]
- Legal description of the property, as registered with Land Title and Survey Authority of BC
- A copy of the current land registration, including Covenants
- A copy of the existing survey plan of the property; the Client may need to commission a legal survey if none exists (this may require a BC Land Surveyor)
- For building permit, details about the location of the building site, and for subdivision, details about the proposed subdivision plan and proposed building sites[4]
- For Construction, plans of existing buildings or structures, and location of the proposed Construction on the ground
- For Construction, proposed Construction drawings
- Locations of existing, proposed, and anticipated Elements at Risk on and, if required, beyond the property
- In general terms, proposed and anticipated land use changes on and, if required, beyond the property (e.g., forestry; other land developments)[5]
- Information on past or existing Landslide problems, or potentially unstable slopes
- Recognition that the Landslide Assessment is based on the proposed development and changes to that development plan may require changes to, or invalidate, the Landslide Assessment
- Relevant background information (written or otherwise) related to the property and the existing and proposed development, including previous Landslide Assessment Reports conducted for the Client or available to the Client

[3] In this regard, a QP should consider beginning an assignment only after the Client has applied to, and received a response from, the approving jurisdiction for the proposed Residential Development.
[4] Subdivision and construction planning are iterative processes, and therefore proposed plans may not be produced until the results of the Landslide Assessment are known.
[5] It is recognized that a private Landowner may not be aware of upslope/upstream watershed changes unless they are obvious or have been advertised.

The QP should enter into a professional services Agreement with the Client prior to undertaking work on the project. Some specific points for consideration regarding the Agreement are as follows:

- In recognizing that natural hazards projects inherently have high potential liability, the Agreement should consider approaches for managing liability risk between the parties.
- The Agreement should confirm the scope of services to the extent that it is known at the time of the Agreement (natural hazards projects typically involve several scope modifications during the project, which should be documented). The scope of those services must take into consideration the requirements imposed by probabilistic life safety criteria, where those are mandated by bylaws or policy created by Local Government, and must include methodologies that can clarify the natural or induced hazard. The Agreement should address if procurement of third-party review is part of the scope of services and, if not, should clarify who is responsible for procuring any required third-party reviews.
- The Agreement should dictate that the Landslide Assessment Report may only be relied upon for the project for which it was prepared.
- The Agreement should establish a budget estimate, either for hourly services, lump sum, or otherwise (recognizing that modifications to scope will typically impact the budget).

The QP should inform the Client that the QP's cost estimate may have to be amended during the assessment, depending on the QP's findings and analysis. The Client should also be informed that a Landslide Assessment does not guarantee the results will be favourable for the proposed development. The cost estimate and likely results should be discussed with the Client prior to the assignment.

The Agreement should also include a clause that addresses potential disclosure issues due to the obligation of the QP under the Engineers and Geoscientists BC Code of Ethics Principle 1 (hold paramount the safety, health, and welfare of the public, and the protection of the environment, and promote health and safety in the workplace). In certain circumstances, the QP may have to convey adverse Landslide Risk assessment findings to parties who may not be directly involved but who have a compelling need to know. The following is suggested wording for such a clause:

> "Subject to the following, the Qualified Professional (QP) will keep confidential all information, including documents, correspondence, reports, and opinions, unless disclosure is authorized in writing by the Client. However, in keeping with the Engineers and Geoscientists BC Code of Ethics, if the QP discovers or determines that there is a material risk to the environment or the safety, health, and welfare of the public or worker safety, the QP shall notify the Client as soon as practicable of this information and the need that it be disclosed to the appropriate parties. If the Client does not take the necessary steps to notify the appropriate parties in a reasonable amount of time, the QP shall have the right to disclose that information to fulfil the QP's ethical duties, and the Client hereby agrees to that disclosure."

During the Landslide Assessment, the Client should support the QP in the following ways:

- Show the QP the locations of legal property boundary markers on the ground and location of the development
- Allow the QP unrestricted access to the property
- Obtain access, if required, to areas beyond the property, as Landslide sources may, in some cases, be kilometers or tens of kilometers upslope or upstream of the development

After the Landslide Assessment the Client should consider completing the following activities:

- Review the Landslide Assessment Report and understand the limitations and qualifications that apply

- Discuss the report with the QP and seek clarification, if desired
- Direct the QP to complete a Landslide Assessment Assurance Statement (Appendix D)
- Provide the Statement and the Landslide Assessment Report to the Approving Authority
- If related to a building project, allow the QP to coordinate with and support the work of the geotechnical engineer of record for the building project, particularly in relation to Item 8.4 (Structural considerations of soil, including slope stability and seismic loading) in the Schedule B Letters of Assurance under the *BC Building Code* (*BCBC*)
- Notify the QP if land use, site development, or slope conditions change or vary from those described in the report

2.2.2 QUALIFIED PROFESSIONAL

The QP is an Engineering/Geoscience Professional with the appropriate level of education, training, and experience to conduct Landslide Assessments as described in these guidelines. A QP may practice professional engineering and/or professional geoscience in the profession(s) in which they are registered.

The QP is responsible for collaborating on scope definition or level of effort (Appendix B: Landslide Assessment – Determining the Level of Effort); for executing the Landslide Assessment; and, if required, for making recommendations to reduce the likelihood of Landslides and/or Consequences.

Prior to carrying out a Landslide Assessment the QP should:

- be knowledgeable about the application and approval process, the procedures for subdivision approvals, development permits, building permits, and exemptions, and the requirements of applicable legislation;
- be aware of and well-versed in the relevant literature pertaining to the study site and the hazard phenomenon in question;
- provide the Client with information from Engineers and Geoscientists BC (such as these guidelines), to help the Client understand their own and the QP's responsibilities;
- confirm that they have appropriate training and experience to design and execute a Landslide Assessment associated with the complexity of the project terrain and geology and, if not, involve required specialists;
- obtain a copy of the approving jurisdiction's guidelines for carrying out Landslide Assessments and/or for preparing Landslide Assessment Reports (if they exist);
- obtain the adopted Level of Landslide Safety, or other Landslide Assessment approval criteria, for the proposed development in the approving jurisdiction or, if those do not exist, use existing adopted Levels of Landslide Safety in BC or other jurisdictions globally for comparison;
- be mindful of the entirety of the potential geomorphic footprint of the hazards under consideration, by assessing secondary effects or cascading hazards, both upstream/upslope or downstream/downslope of the building site, and clarify with the Client and Approving Officer in what way those effects should be included in the Landslide Assessment; and
- discuss with the Client and Approving Officer the maximum return period considered in a hazard or risk assessment and the implications for residual risk.

The QP should enter into an Agreement with the Client for the work to be performed, as described in Section 2.2.1 Client. The QP must comply with the requirements of Engineers and Geoscientists BC Bylaw Section 7.5 regarding professional liability insurance.

During the Landslide Assessment, the QP should:

- assist the Client in obtaining relevant information, such as that listed in Section 2.2.1;
- make reasonable attempts to obtain from the Client and others all relevant information related to the

slope stability of the property itself and, if required, beyond the property;

- conduct field work within the limits of the property itself and, if necessary, beyond the property at an intensity appropriate to the required level of effort (Appendix B) of the Landslide Assessment;
- conduct the Landslide Assessment in compliance with all applicable codes and regulations;
- consider both Landslides and their Consequences on the development, and the Consequences of the development on Landslides on the property itself and, if required, beyond the property;
- notify the Client as soon as reasonably possible if specialty services or changes in scope of work are required, and of associated changes to the original cost estimate;
- write the report clearly, concisely, and completely, and conform to all applicable guidelines for Landslide Assessment Reports;
- have a draft of the report appropriately peer reviewed;
- submit to the Client a signed, sealed, and dated copy of the report;
- complete a Landslide Assessment Assurance Statement, and where required provide the Statement and the Landslide Assessment Report to the Approving Authority;
- with respect to proposed protective measures, identify the nature of any required follow-up work, including required coordination with Approving Authorities necessary to determine the nature of future or ongoing professional oversight; and
- consult with the Approving Authority regarding field review, post-Construction reporting, and operations and maintenance plans for the proposed protective measures.

After the Landslide Assessment, the QP should:

- reasonably respond to all questions the Client and/or Approving Authority may have regarding the Landslide Assessment, Landslide Assessment Report, and/or Landslide Assessment Assurance Statement;
- address editorial comments; and
- if required, and in agreement with the Client and/or Approving Officer, modify the scope and carry out follow-up work.

If aspects of the Landslide Assessment are delegated, they should only be carried out under the direct supervision of the QP. The QP assumes full responsibility for all work delegated (refer to Section 4.1.3 Direct Supervision).

According to the Engineers and Geoscientists BC Code of Ethics, Principle 10, Registrants should clearly indicate to their Client any possible Consequences if the QP's recommendations are disregarded.

If a Client fails or refuses to accept the conclusions and recommendations of the Landslide Assessment Report, the QP should:

- advise the Client in writing of the potential Consequences of the Client's actions or inactions (see the Code of Ethics, Principle 10);
- consider advising the Client to contact Engineers and Geoscientists BC's Practice Advice Program regarding any questions about the QP's role or these guidelines; and
- consider whether the situation warrants notifying Engineers and Geoscientists BC, the Landowner (if different from the Client), and/or the appropriate authorities (see the Code of Ethics, Principle 9).

The actions associated with the above three bullets should be taken, particularly if loss of life and/or other substantial negative Consequences are possible, or if workplace safety or the environment is jeopardized, in recognition of the Code of Ethics, Principle 1.

2.2.3 APPROVING AUTHORITY

For legislated Landslide Assessments, the Local Government or the provincial government typically triggers the requirement for an assessment and is the Approving Authority. As previously noted, an Approving Authority can be an Approving Officer, a Building Inspector, or a planner and/or council/board of a Local

Government. Once triggered, most Landslide Assessments are carried out for the Owner or the Development Consultant.

Before the Landslide Assessment is initiated, it is helpful if the Approving Authority facilitates a fulsome assessment process by:

- being familiar with the Municipal Insurance Association of British Columbia's document *Guidelines for Planners, Approving Officers and Building Inspectors for Landslide-Prone Areas in British Columbia* (Skermer 2002);
- providing information in writing to the Client as to why a Landslide Assessment is required;
- providing to the Client the adopted Level of Landslide Safety for various development types in the approving jurisdiction, if applicable; and
- providing the Client in writing with jurisdiction-specific guidelines, requirements, or administrative procedures, if they exist, that affect the work of a QP tasked in carrying out a Landslide Assessment and/or preparing a Landslide Assessment Report.

After the Landslide Assessment is received, the Approving Authority is expected to review the Landslide Assessment Report and the Landslide Assessment Assurance Statement and seek clarification regarding the report contents from the QP, where necessary.

An Approving Authority may request that an independent QP (a peer reviewer) be engaged to carry out a review of the Landslide Assessment Report and the Landslide Assessment Assurance Statement. Less frequently, a Client may ask for such a review. In the absence of a clear policy by the Approving Officer, the scope of the peer review and the remuneration of the peer reviewer should be clarified between the QP, the Approving Authority, and the Client at the onset of a new project. (See also Section 2.2.4.)

2.2.4 PEER REVIEWER

Upon request of an Approving Authority or a Client, or on their own initiative, a QP may submit their Landslide Assessment Report for peer review by another QP (the "peer reviewer"). Following the Code of Ethics, Principle 13, the peer reviewer should:

- ask the QP who prepared the report whether there are any unreported circumstances that the peer reviewer should know about that may have limited or qualified the Landslide Assessment, the Landslide Assessment Assurance Statement, and/or the report; and
- with the Client's authorization, contact the QP who prepared the report and Landslide Assessment Assurance Statement, if the results of the peer review identify safety or environmental concerns, in order to allow the opportunity for the QP to comment prior to further action being taken.

The peer review should be appropriately documented in a letter or a report. The peer reviewer should submit an authenticated (signed, sealed, and dated) letter or report, including:

- limitations and qualifications with regards to the peer review; and
- results and/or recommendations arising from the peer review.

The peer reviewer should respond to any questions the Approving Authority or Client may have with regards to the letter or report. The requesting Approving Authority or Client should be aware that Principle 13 of the Code of Ethics generally governs Registrant behaviour regarding peer review.

This generally means that a QP should, where practicable:

- provide the peer reviewer with a copy of the Landslide Assessment Report and Landslide Assessment Assurance Statement, necessary background information, and the reason for the peer review;

- review the peer review letter or report; and
- if necessary, discuss the peer review letter or report with the peer reviewer and seek clarification.

Occasionally, a QP is retained to provide a second opinion. This role goes beyond that of peer review of the work of the original QP. In such a situation, the second QP should carry out sufficient pre-field work, field work, analysis, and comparisons, as required, to provide a fully separate Landslide Assessment, and to accept full responsibility for that Landslide Assessment.

See also the *Professional Practice Guidelines – Peer Review* (Engineers and Geoscientists BC 2022).

2.2.5 INDEPENDENT REVIEWER

As clarified in Section 4.1.7 Documented Independent Review of High-Risk Professional Activities or Work and Appendix C: Review of Levels of Landslide Safety, any Landslide Assessments that are not considered Class 0 should be classified as "high risk." Therefore, according to the Engineers and Geoscientists BC Bylaws and quality management standards, an independent review of the Landslide Assessment Report must be carried out prior to submitting the report to the Client and/or the Approving Authority.

The scope of the independent review must be consistent with the requirements outlined in Section 4.1.7 Documented Independent Review of High-Risk Professional Activities or Work. Note that the independent reviewer must clearly define the scope and limitations of the independent review.

Further details regarding the role of an independent reviewer are available in Section 4.1.7 of these guidelines and the *Quality Management Guides – Guide to the Standard for Documented Independent Review of High-Risk Activities or Work* (Engineers and Geoscientists BC 2021c).

3.0 GUIDELINES FOR PROFESSIONAL PRACTICE

3.1 INTRODUCTION

This section provides guidance on the components of Landslide Hazard and Landslide Risk assessments (shortened to "Landslide Assessments" in this document). The requirements of Landslide Assessments for non-legislated and existing developments, as well as those of legislated and proposed Residential Developments, are included in these guidelines.

- **Legislated Landslide Assessments** are explicitly required by provincial or national enactments, including those listed in Appendix A: Legislative Framework.
- **Non-legislated Landslide Assessments** may be performed based on local or regional government development and permitting policies, or may be initiated at the request of a property owner, stakeholder, or rightsholder.

These guidelines are not intended to provide technical or systematic instructions or to explain the individual methods for how to conduct Landslide Assessments; rather, these guidelines outline considerations to be aware of when carrying out these activities. Qualified Professionals (QPs) must exercise professional judgment when providing professional services; as such, application of these guidelines may vary depending on the circumstances. For information on how a QP can appropriately depart from the guidance provided in these professional practice guidelines, see Section 4.1.1 Use of Professional Practice Guidelines.

3.1.1 CONSIDERATION OF RISK

The goal of any Landslide Assessment is to prevent or reduce potential harm to people or infrastructure that could be affected by a Landslide near or resulting from proposed and existing developments. As used in these guidelines, the term "Level of Landslide Safety" includes levels of acceptable Landslide Hazard and Landslide Risk (as adopted or imposed).

Levels of Landslide Safety with respect to life loss are determined by society, not individuals. Therefore, for developments that expose human life to Landslide Risk, the levels must be established and adopted by the Local Government or the provincial government after consideration of a range of societal values. With respect to property damage or purely economic loss, the level of acceptable loss should be established by the Client who stands to lose. A QP should not be expected to establish a Level of Landslide Safety or acceptable economic loss, although the QP may advise the Client, the Local Government, or the provincial government in that regard.

The QP has a professional responsibility to uphold the principles outlined in the Engineers and Geoscientists BC Code of Ethics, including protection of public safety and the environment. As such, the QP must use a documented approach to identify, assess, and mitigate risks that may impact public safety or the environment when providing professional services.

One of the risk factors that must be considered is climate change implications. QPs have a responsibility to notify their Clients of future climate-related risks, reasonable adaptations to lessen the impact of those risks, and the potential impacts should a Client refuse to implement the recommended adaptations. QPs are themselves responsible for being aware of and meeting the intent of any climate change requirements imposed by a Client or an authority having jurisdiction.

Other areas of risk encountered in professional practice are quality, technical, financial, and commercial risks. QPs should consider risks in such areas using techniques that are appropriate to their area of practice, and should recommend that the Client retain an appropriately qualified individual for areas outside of their training and experience.

3.2 STUDY TYPES

Numerous types of Landslide Assessments exist, ranging in complexity from relatively simple office-based reviews of air photographs, and satellite and LiDAR images, to comprehensive multi-year studies in which several surface and subsurface observations are evaluated and integrated into a hazard and risk assessment.

Accordingly, the costs of such studies range from a few thousand to millions of dollars, especially when subsurface investigation and instrumentation is required.

This section provides guidance regarding what level of effort is needed for performing Landslide Assessments for existing and new developments. Figure 1 provides guidance on how to select the correct type of study and how the different types of studies are interconnected. In addition, QPs must inform themselves on the specific requirements for their particular project, whether legislated or non-legislated.

The content of the following subsections is summarized from the document *Landslide Risk Evaluation – Canadian Technical Guidelines and Best Practices Related to Landslides: A National Initiative for Loss Reduction* (Porter and Morgenstern 2013), to provide guidance to QPs when selecting an appropriate type of study.

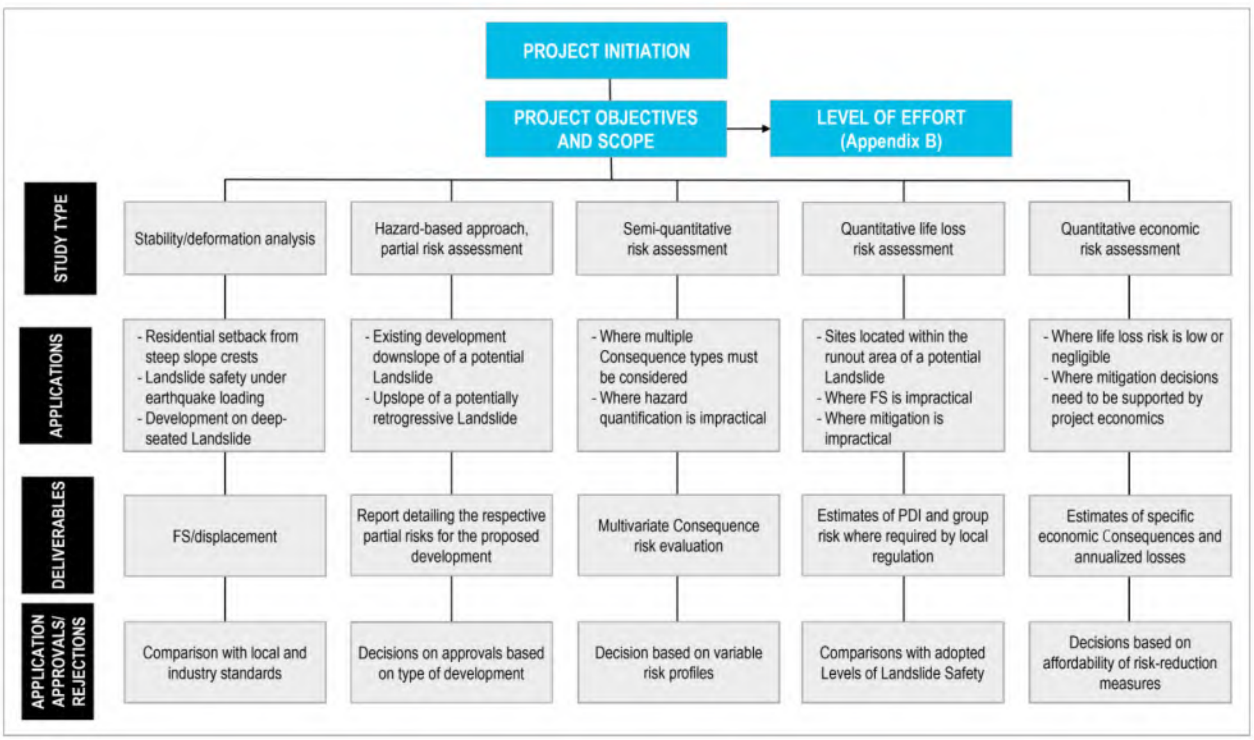

Figure 1: Flowchart illustrating types of Landslide Assessments and their application

NOTES:
Abbreviations: FS = Factor of Safety; PDI = annual probability of death to an individual

3.2.1 SLOPE STABILITY AND DEFORMATION ANALYSIS

Limit equilibrium slope stability analyses can be used to obtain reliable estimates of the Factor of Safety where the kinematic failure mode of instability is understood, and where the basic model input parameters, such as stratigraphy, shear strength, groundwater conditions, and external loads, can be determined with reasonable accuracy.

Slope stability analysis can be used:

- to support the selection of development setback guidelines from the crest and the toe of potentially unstable slopes, considering the potential for future erosion (or other destabilizing actions) where appropriate;
- in conjunction with liquefaction susceptibility and lateral spreading or deformation analyses, to assess the Level of Landslide Safety under earthquake loading scenarios; and
- to help assess and manage the Level of Landslide Safety where it is determined that development is situated on a pre-existing deep-seated Landslide.

The observational method, by which predicted ground conditions and slope behavior are made in advance and verified during site exploration and slope analysis efforts, helps minimize the effects of parameter, model, and human uncertainty (Morgenstern 1995). When used in conjunction with the observational method, with few exceptions slope stability analyses have been applied successfully to the design and management of “engineered” slopes such as cuts, embankment fills, and retaining walls, and for the design of structures located on or at the crest or the toe of potentially unstable slopes.

3.2.2 HAZARD-BASED APPROACH AND PARTIAL RISK ASSESSMENTS

Partial risk is also defined as the product of the probability for a specific hazardous Landslide, and the probability of that Landslide reaching or otherwise affecting a considered element. Partial risk does not account for the vulnerability of the Element at Risk or the Consequences of the event (Wise et al. 2004). Where existing or proposed development is located downslope (not on the slope itself) of a potential Landslide, or upslope of a potential retrogressive Landslide, partial risk (also known as encounter probability) can offer a suitable means of evaluating Landslide safety.

This approach has been applied in some jurisdictions for several decades (e.g., the Fraser Valley Regional District; Cave 1993). Note that following Cave (1993), threshold frequencies are typically varied according to the destructiveness of the hazard and the type of development being considered (FVRD 2020). This introduces a measure of Consequence into the assessment.

The application of partial risk criteria is conservative, whereby if the hazardous event reaches the site at or more frequently than the threshold frequency, then the acceptability threshold is exceeded without consideration of the timing of exposure for, vulnerability of, and value placed on the Elements at Risk. In these cases, the residual risk of loss of life can be mitigated by the design, construction, and maintenance of physical barriers such as ditches, berms, basins, catch nets, or walls. Moreover, in such cases, application of quantitative risk assessment will provide a more nuanced assessment for design of such measures. Thus, partial risk assessment is best suited where the encounter probability is clearly less than the threshold dictated by the Approving Authority or adopted for the study.

3.2.3 SEMI-QUANTITATIVE RISK ASSESSMENTS

These types of assessments are particularly well-suited for projects where there are several types of Consequences that must be considered in assessing total risk as well as evaluating the need for, and suitability of mitigation measures. Consequence categories include safety, economics, reputation, environmental, archeological/traditional/cultural, and societal well-being. This type of assessment is also useful in situations where detailed quantification of all hazard variables is impractical and order-of-magnitude estimates are appropriate, particularly where risk comparisons are more important than the precise risk estimates.

Examples of projects where a semi-quantitative approach may apply well to a development include:

- post-disaster buildings that provide critical services during and after a significant adverse event;
- event or recreational venues where the number or persons on site can vary significantly; or
- although outside of the direct scope of these guidelines, linear infrastructures (e.g. pipelines, roads, railways, powerlines) or urban developments on, below, or upslope from potentially retrogressing Landslides, where Consequences other than life loss dominate the risk profile.

Using this approach, risks can be qualified from very low to very high, allowing an Approving Officer to decide at what threshold mitigation is required, or if a proposed development cannot be permitted. The approach allows a QP to support the decision that a proposed development is (or is not) “safe for the use intended” per the *Land Title Act* and the *Community Charter*. For semi-quantitative as well as quantitative risk assessment, the justification of input and a description of uncertainties is critical.

3.2.4 QUANTITATIVE RISK ASSESSMENTS

3.2.4.1 QRAs for Loss of Life

For some situations, it may be more appropriate to conduct a quantitative evaluation of the risk of loss of life and encourage the Approving Authority, in collaboration with the QP, to compare the results against published Landslide safety criteria.

These special situations can involve:

- sites located at the toe of slopes or in the potential Landslide runout zone;
- sites where it is impractical to demonstrate that the Factor of Safety for all Landslides exceeds established acceptance criteria; and
- sites where providing for physical protection against all credible Landslide effects is impractical.

Quantitative risk assessments (QRAs) for loss of life are a tool to determine if a development (existing or proposed) meets specific individual risk or group risk tolerance criteria. The life-loss QRA is also used to determine the scope and scale of mitigation measures. Appendix F: Evolving Practice, subsection F.2 Quantitative Risk Assessments of these guidelines provides additional information on life-loss Landslide QRAs.

In Canada, Landslide QRAs are gaining popularity amongst consultants and decision-makers because they are transparent and replicable while providing a clear standard for risk tolerance/acceptance. These guidelines and others, such as the following federal and provincial guidelines, encourage the use of QRAs in Landslide Risk management:

- *Landslide Risk Case Studies in Forest Development Planning and Operations*, BC Ministry of Forests, Land Management Handbook 56 (Wise et al. 2004)
- *Canadian Technical Guidelines and Best Practices Related to Landslides: A National Initiative for Loss Reduction*, published by Natural Resources Canada (Porter and Morgenstern 2013)
- *Land Procedure – Landslide Risk Management*, published by the BC Ministry of Forests, Lands, Natural Resources, and Rural Development (BC MFLNRORD 2014)
- *Draft Guidelines for Steep Creek Risk Assessments in Alberta*, published by Alberta Environment and Parks (Alberta Environment and Parks 2017)

The main advantage of QRAs is their ability to compare results across different hazard types and scenarios, which can facilitate higher-level decision making and improved resource allocation. For example, from a higher-level planning perspective, QRAs allow for a direct comparison of risks between different hazard locations, which permits a prioritization of sites with often disparate Landslide Hazards and allows direct comparison between different risk reduction options. Similarly, Landslide QRA results can be compared to other natural hazards so that available mitigation funds can be distributed equitably.

A potential disadvantage of QRAs is that they purport a sense of precision and accuracy that is not warranted unless error sources are quantified and integrated in the analysis. This, however, is challenging as the individual errors are sometimes not quantifiable.

A QRA may be conducted for the individual or for groups. In practice, for Level 0/1 studies (Appendix B: Landslide Assessment – Determining the Level of Effort), life-loss risk to individuals (annual probability of death to an individual, or PDI) may be required, but typically not group risk. For Level 2 studies, PDI is required, and group risk calculations are optional. For Level 3 studies, both PDI and group risk need to be estimated. For proposed or existing developments, it may be prudent that the Approving Authority compares estimates of individual and group risk within a community to ensure consistency of risk management objectives at the societal level (Evans and Verlander 1997).

Deciding when to estimate only life-loss risk versus other risks such as economic, environmental, or even sociopolitical risks, depends on the scope of work provided to the QP by the Client and regulated by legislation, bylaws, or other enactments. Inclusion of such risks may be optional but can help the Client or Approving Officer in their Landslide Hazard and Landslide Risk management decisions.

3.2.4.2 QRAs for Economic Risks

Economic risks can be estimated quantitatively with reasonable accuracy. Importantly, these QRAs allow integration into risk cost-benefit analyses that are a critical tool when considering options that inform selection of a Landslide Risk reduction strategy. These types of assessments can be useful in supporting any decision on mitigation but also land-use zoning.

Examples for when a Landslide QRA is used to assess economic risks include:

- when life loss and total, incremental, or annualized economic losses are being evaluated to optimize mitigation measures;
- when Landslides are deep-seated and slow moving and are unlikely to lead to fatalities but can lead to substantive direct (home damage) or indirect (infrastructure damage) economic losses; and
- when insurability is being examined for developments on existing slow-moving Landslides or within the potential runout zone or retrogression areas.

While there are no formal economic risk-tolerance criteria, economic QRAs greatly aid in deciding if mitigation is cost effective, and what mitigation measures will maximize cost efficiency. This practice is common, for example, in Switzerland, Austria, Italy, and France.

3.3 LANDSLIDE ASSESSMENTS

The following subsections provide practice guidance for the various phases in Landslide Assessment.

3.3.1 RISK MANAGEMENT FRAMEWORK

Risk management frameworks are well established (e.g., ISO 31000), and generally include the stages described in Table 1; this system should be followed as much as possible to provide a consistent approach.

These guidelines define a hazard as “a source of potential harm, or a situation with a potential for causing harm, in terms of human injury; damage to health, property, the environment, and other things of value; or some combination of these.” Landslide Risk considers both Landslide Hazard and potential Consequences to Elements at Risk (elements of social, environmental, and economic value, including human well-being and property).[6]

[6] Other definitions of hazard and risk exist. The choice of definitions rests with the QP, although the definitions should be included in the Landslide Assessment Report.

Table 1: Example Risk Management Framework

<table>
<tr><th colspan="5">ASSESSMENT TYPE</th><th rowspan="8">RISK COMMUNICATION AND CONSULTATION
Informing stakeholders about the risk management process</th><th></th><th rowspan="8">MONITORING AND REVIEW
Ongoing review of risk scenarios and risk management process</th></tr>
<tr><td rowspan="2">ASSESSMENT</td><td rowspan="3">RISK IDENTIFICATION</td><td rowspan="4">RISK ESTIMATION</td><td rowspan="5">RISK ASSESSMENT</td><td rowspan="7">RISK MANAGEMENT</td><td>1. PROJECT INITIATION
a. Recognize the potential hazard
b. Define the study area and level of effort
c. Define roles of the Client, regulator, stakeholders, and Qualified Professional (QP)
d. Identify ‘key’ Consequences to be considered for risk estimation</td></tr>
<tr><td>2. GEOHAZARD ANALYSIS
a. Identify the geohazard process
b. Characterize the geohazard in terms of factors such as mechanism, causal factors, and trigger factors
c. Estimate frequency and magnitude
d. Develop geohazard scenarios
e. Estimate extent and intensity of geohazard scenarios</td></tr>
<tr><td>3. ELEMENTS AT RISK ANALYSIS
a. Identify Elements at Risk
b. Characterize Elements at Risk with parameters that can be used to estimate vulnerability to geohazard impact</td></tr>
<tr><td>4. RISK ANALYSIS
a. Develop geohazard risk scenarios
b. Determine geohazard risk parameters
c. Estimate geohazard risk</td></tr>
<tr><td>5. RISK EVALUATION
a. Compare the estimated risk against tolerance criteria
b. Prioritize risks for risk control and monitoring</td></tr>
<tr><td>6. RISK CONTROL DESIGN
a. Identify options to reduce risks to levels considered tolerable by the Client or governing jurisdiction
b. Select option(s) with the greatest risk reduction at least cost
c. Estimate residual risk for preferred option(s)</td></tr>
<tr><td>7. RISK CONTROL IMPLEMENTATION AND MONITORING
a. Implement chosen risk control options
b. Define and document ongoing monitoring and maintenance</td></tr>
</table>

A Landslide Assessment is a combination of:

- Landslide analysis, which involves recognition, characterization, and estimation of the hazard, and may include estimation of potential Consequences; and
- evaluation by comparing the results of the analysis with a Level of Landslide Safety.

The principles of the Landslide Risk management framework apply to the Factor of Safety (FS) analysis for individual slopes, as well as to scenarios where hazards beyond the site may affect the development.

3.3.1.1 Phases of a Landslide Assessment

A complete Landslide Assessment typically involves the following phases:

- Initiating the assessment, including determining objectives, likely Landslide type(s), type of Landslide Assessment, and level of effort
- Defining the site, study area, and consultation zone (see Figure 2)
- Collecting and reviewing background information
- Conducting fieldwork, ranging from visual mapping to detailed specialty investigations, depending on the level of effort
- Conducting the Landslide Hazard or Landslide Risk analysis
- Comparing the results of the Landslide analysis with a Level of Landslide Safety
- Providing recommendations, if requested, to reduce Landslide Hazards and/or Landslide Risks
- Writing and submitting a Landslide Assessment Report

3.3.1.2 Level of Effort

The objective of this section is to provide guidance to the QP tasked with developing a scope of work for conducting a Landslide Assessment. (See also Appendix B: Landslide Assessment – Determining the Level of Effort.)

Consistency amongst QPs with respect to the level of effort expended for a given Landslide Assessment is important. For large-scale projects, the request for proposal document typically describes a succinct scope of work that governs the level of effort expected from the QP. However, for the majority of Landslide Assessments, the QP must define the appropriate level of effort. QPs must be careful to select a level of effort that is appropriate to the nature of the hazards and risks applicable to the site. In particular, QPs must be cautious that preliminary assessments of a site that provide opinions as to suitability to proceed to the next development stage are not used in place of the full level of effort required to provide conclusions as to the suitability of the site for the use intended.

The level of effort for a Landslide Assessment depends on both the increased risk introduced by the type of proposed project (e.g., building renovation versus subdivision Construction), and on the scale and complexity of the potential Landslide and auxiliary hazards[7] (that is, whether there is risk of injury or death and the likely degree of economic loss).

For a given level of effort, the QP must be able to defend the methodology and report findings with sound rationale. A summary of recommended levels of effort considered appropriate for a given project scope are provided in Appendix B: Landslide Assessment – Determining the Level of Effort.

The tables in Appendix B describe the different scales of risk exposure and development. Frequency-magnitude (F-M) relationships that extend into thousands of years require a high level of effort and may not be feasible, due to incompleteness of the sedimentary archive or limitations on developing a geochronology. Further, F-M analysis uncertainties increase proportionally with return period (due to data paucity) such that, in most cases, for rare hazards the uncertainty bounds become too large to meaningfully apply the estimate.

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[7] Auxiliary hazards are second-order effects of Landslides, such as upstream flooding, Landslide dam outbreak floods, or liquefaction failure of the substrate onto which the Landslide has fallen.

3.3.2 LANDSLIDE ANALYSIS

3.3.2.1 Site, Study Area, and Consultation Zone

Landslide Assessments are carried out for a specific site or parcel of land, but the terrain that requires assessment is typically more extensive because the adjacent geomorphology, hydrology, and engineering geology must be understood, to connect landforms to geomorphic process and vice versa.

It is important to differentiate between the "site," the "study area," and the "consultation zone":

- **Site**: typically the footprint of the development site and immediately adjacent areas
- **Study area**: the area around the development site, in which geomorphic processes are acting that could affect the site
- **Consultation zone**: the area affected by the largest credible event, or combination of scenarios, considered in the assessment; the consultation zone is typically larger than the site but smaller than the study area (see Figure 2)

For assessments of any size, these terms and their application should be defined and clarified as soon as the assessment is initiated.

As shown in Figure 2, for Landslide Assessments of sites affected by all types of upslope hazards (e.g., rock avalanche, rockfall, debris slide, debris flow, retrogressive slide), the study area must include the hillslope or watershed area above the site, as this would be the source of water and sediment.

Some types of Landslides can travel long distances. Therefore, if Landslides from remote sources (e.g., upper watershed areas, glacial lakes, dammed lakes, volcanoes) could possibly affect the proposed development, the study area should also include those areas. Also, the potential for cascading hazards must be considered. For example, during a Landslide damming event, flooding can extend kilometres upstream of the consultation zone, and even further downstream should the Landslide dam rupture catastrophically.

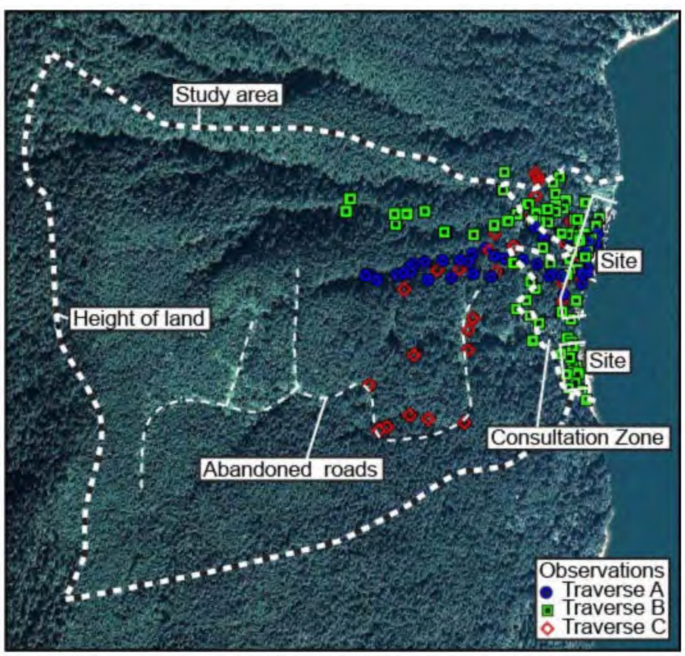

Figure 2: Example of a map showing the spatial relations between a site, the study area, and the consultation zone

NOTES: In this figure, the study area consists of the upslope area affecting the site, and the consultation zone, which is the area affected by a combination of events, in this case debris cones at the base of a slope.

3.3.2.2 Background Information

Prior to fieldwork, the QP should collect and review, with the help of the Client where appropriate, available existing information associated with the study area. The QP should consider and suitably reference the following information, and their respective levels of reliability, as possible sources of existing information:

- Large- and small-scale topographic and cadastral maps
- Maps that show existing and proposed infrastructure, such as transportation routes, utilities, surface drainage, in-ground disposal of stormwater, and in-ground disposal of wastewater and/or sewage
- Air photos, LiDAR images, and/or satellite images of different years (historical to present) and scales
- Terrain maps, terrain stability maps, Landslide inventories, Landslide Hazard maps and reports
- Data on bedrock and surficial geology
- Seismic data, including seismic hazard maps and reports, Ground Motion data, seismic site class, and modal magnitude values of the design earthquake
- Water-well records and hydrogeology reports
- In areas of logging, information such as forest cover maps, forest development/stewardship plans, watershed assessments, terrain stability assessments, data on existing and proposed forest road networks, and other relevant logging-related land-use information
- In areas of mining, information such as existing and proposed mining plans, descriptions of underground works, data on slope instabilities associated with mining activities, and descriptions of upstream tailings dams
- Floodplain maps and alluvial fan maps
- Evidence and history of wildfires and insect infestation in the area
- Other resource inventory maps and reports
- Descriptions of previous development, including residential and non-residential, and associated infrastructure
- Previous geological, geotechnical, and Landslide Assessment Reports that address the study area and, if available, neighbouring areas
- Anecdotal information from long-term residents and media reports

If some basic background information is lacking, it may be necessary to purchase project-specific resources (e.g., air photos, satellite and LiDAR imagery).

Landslide Assessment Reports from neighbouring areas can be useful to the QP. The Fraser Valley Regional District has compiled a library of all existing hazard reports (site-specific and overview) and requires QPs to review those that are pertinent to a proposed development. Provincial government and Local Governments may also make such reports available to a QP. In all cases, it is the QP's responsibility to identify and request background information from regulatory agencies.

Information can also be obtained from published and unpublished sources available from various federal and provincial agencies, Local Governments, and other local sources. In BC, the reports by Septer (2007a; 2007b) are a useful resource that catalogue historic damages from floods and Landslides from media reports from early colonial settlement to up to 2006.

3.3.2.3 Fieldwork

The scope of fieldwork is governed by the identified level of effort (Appendix B) and by the results of the background review, which provide preliminary insight on terrain conditions, hazard identification, characterization of potentially unstable slopes, Landslides, and Elements at Risk. Despite the continuing improvement of precision remote-sensing and change-detection tools, Landslide Hazard assessments continue to rely on fieldwork.

The QP must exercise professional judgment when determining the intensity of fieldwork and the specific areas to visit in the field. However, to reasonably standardize approaches, the guidance in Appendix B should be followed; where the QP determines that it is necessary to deviate from that guidance, the rationale should be justified and documented by the QP.

Fieldwork should consider different types of Landslides and potentially unstable slopes within and, if required, beyond the proposed or existing development. Rugged or difficult-to-access terrain or inclement weather should not deter required fieldwork in areas with questionable slope stability, unless there are safety concerns; in that case, helicopter support or drones could be engaged to view inaccessible or safety-challenged sites. As part of determining supporting rationale, fieldwork should review areas of past instability and should assess the possible causes of such instability.

Complex geological conditions can have a profound effect on slope stability, and frequently such geological complexity is hidden. The QP should recognize the potential for slope instability, which can be initially based on local experience and review of imagery, but typically also requires experienced, quality fieldwork including subsurface investigations (e.g., geophysics, drilling, and various instrumentation).

The QP must appropriately record field observations and results of field investigations. Written notes, ground photographs, stereo ground photographs, videos, global position system (GPS) waypoints, drill logs, and various instrumentation outputs all may be considered means of documentation.

If specific areas have been determined, or if a building envelope or Covenant boundary is to be recommended, temporary survey markers should be located and appropriately labelled during fieldwork. The QP should consider recording these areas or sites by means of photographs (with temporary survey markers in place) or as GPS waypoints (with appropriate tolerance for locational error). Increasingly this is being done via digital devices that record the location and observations at the same time.

Landslide Assessment depends on a QP's skills and experience in observing and evaluating underlying geological conditions. The delegation of fieldwork to a less-experienced engineer, geoscientist, technologist, or technician, under the supervision of a QP, should be done according to the requirements and expectations for direct supervision (refer to Section 4.1.3 Direct Supervision).

3.3.2.4 Process Identification and Hazard Scenario Development

A Landslide Hazard analysis is undertaken to review and understand the terrain and geomorphic setting of the Landslide Assessment, and to identify and characterize any hazards and Landslide scenarios (i.e., active, inactive, and dormant) within and, as typically required, beyond the proposed development.

Landslide Hazard can be estimated in various ways, including, but not limited to, the following:

- Estimating the likelihood or probability of occurrence of a Landslide
- Defining the Factor of Safety (FS) of a slope
- Determining the slope displacement along a slip surface (LE – Limit Equilibrium), or deformation analysis (FE – Finite Element)

As hazard is defined as affecting something of value, the Landslide Hazard must include an estimate of Landslide runout (for development at the bottom of the slope), or an estimate of where the main scarp of the Landslide will intersect the ground (for development on, or at the top of, the slope) through retrogression. The volume, peak discharge, velocity, damage intensity, or some other measure of damage potential is also required.

Landslides can have several conditioning factors, or causes, including geological, morphological, physical, and human (Alexander 1992; Cruden and Varnes 1996), but only one trigger (Varnes 1978). The QP should differentiate between causes and triggers in the assessment report. Landslide causes and triggers are identified by assessing media or anecdotal reports; reviewing weather, earthquake, snowpack, or streamflow records; through back-analysis or deduction;

as well as by direct field observations or on-site or remotely-sensed measurements.

Common Landslide triggers, including intense rainfall, rapid snowmelt, water-level changes, volcanic eruptions, and strong ground shaking during earthquakes, are responsible for most Landslides worldwide. To determine Landslide susceptibility, a valid geological model must be established that also accounts for any artificial or natural slope alterations, as well as surface water and groundwater regimes. This is especially important since poorly designed and/or poorly inspected and maintained surface water management systems, including residential stormwater and resource roads, are the leading cause of Landslides in BC.

3.3.2.5 Hazard Frequency, Probability, and Frequency-Magnitude Analysis

When a project may be affected by hazards originating beyond the site, life safety criteria defined by the BC Ministry of Transportation and Infrastructure (BC MOTI) and some Local Governments specify requirements for annual probabilities or return-period thresholds.

Even for cases where soil slope stability analysis is selected to calculate an FS, the BC MOTI may still require assurance that the return-period safety criteria will be met. To satisfy this criterion, some estimate of the probability of the site being affected is required (see Table 2: Qualitative and Quantitative Hazard Frequency Categories Affecting a Building Site).

If possible, a frequentist approach is used, but in engineering geology the use of judgment that utilizes available data, knowledge, and experience is invariably required (Lee 2009). Ideally, as with Flood Frequency Analysis (FFA), the objective is to develop a graph that relates the frequency of the hazard to its magnitude (Figure 3), which may be expressed using return periods, the inverse, as an annual probability, or, to put it in the perspective of human experience, as a probability of occurrence in n-years (i.e., 1:475 per annum equals 10% in 50 years; Table 2).

A reliable frequency-magnitude (F-M) model extending over a 2,500 to 10,000-year sample frame requires considerable effort and cost to construct, if it is even practicable or possible. As small projects (class 0 to 1) have less available funding, their ability to extend an F-M curve to 2,500 or 10,000 years with any confidence is severely limited.

Where subsurface investigation is not practicable or yields no chronologic data, then thorough surface mapping and observations are the sole chronologic resource. Methods like space-time substitution, expert judgment, or panel review may be required, to obtain probable rates of damaging or potentially lethal events. Space-time substitution refers to compiling Landslide activity over a wide, but similar physiographic, area and deriving a regional frequency estimate to apply at a site. This method is particularly applicable to rock avalanches or debris avalanches, debris slides, and rockslides that, at the site in question, have few or no precedents in the historic record. For example, a steep slope below which a subdivision is proposed may show no signs of debris avalanches on air photographs, but this does not mean it is not susceptible to debris avalanches at a higher return period than the air photograph analysis might suggest. A regional approach would document debris avalanches in similar terrain over a larger area and then apply the findings to the site.

Table 2: Qualitative and Quantitative Hazard Frequency Categories Affecting a Building Site

QUALITATIVE FREQUENCY	ANNUAL RETURN FREQUENCY	PROBABILITY (% IN 50 YEARS)
Very high	>1:20	>90
High	1:100 to 1:20	40 to 90
Moderate	1:500 to 1:100	10 to 40
Low	1:2,500 to 1:500	2 to 10
Very low	<1:2,500	<2

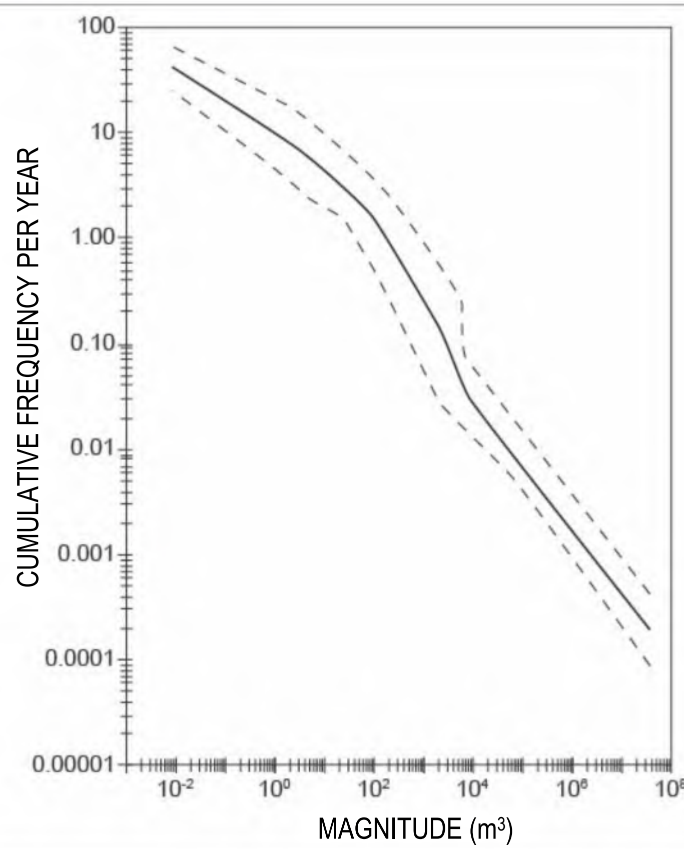

Figure 3: Example of a cumulative frequency-magnitude curve for rockfalls and rockslides along four major transportation corridors in southwestern British Columbia

NOTE: Figure adapted from Hungr et al. (1999)

In this situation, the notion of the "maximum credible hazard" is introduced. Judging the maximum credible hazard relies on experience-based intuition, which has much less accumulated time than the return period specified by life safety criteria. The residual risk may not be properly envisioned, in effect censoring the rare and dangerous end of the F-M model. This could set up what is called a "black swan" scenario.[8] To guard against this, the Landslide Assessment must consider a wide spectrum of risk scenarios, then identify and parse out the low-risk ones.

Given the need for judgment in applied geoscience, the cautionary statement about credible failure assessment is especially meaningful for the lower Consequence projects (class 0 to 1); given that this relies on QP experience, QPs need to be especially careful to remain within their areas of training and experience. However, the risk of a "black swan" could be offset by the notion that those smaller return period hazards envisioned are the ones driving the risk. This balance may not hold for the higher Consequence projects, in which case an expert panel may need to be consulted to reduce the risk of the unexpected (e.g., Cheekye fan expert panel; Clague et al. 2014, 2015).

In some instances, it is important to acknowledge that there are multiple hazards affecting the site. This could be debris floods (a flood process) and debris flows (a Landslide process). Other examples could be rockfall and rockslide processes acting at the same site, or earthflows and concomitant flow slides.

The QP will need to understand the limitations and benefits of various methods and custom tailor those to meet the study's objectives. As noted in Appendix B, the methods to arrive at reliable hazard estimates are related to the scale of the development and associated level of effort.

3.3.2.6 Hazard Cascades

Traditional hazard assessment has focused on discrete hazards in isolation. However, in the last decade it has become increasingly important to identify hazard cascades, alternately referred to as hazard process-chains, domino effects, or multi-hazard assessment.

A hazard cascade occurs when a particular process triggers another or a series of subsequent hazards. With a hazard cascade, the ultimate area impacted reaches far beyond the triggering event, with effects lasting years to decades, and potentially greatly amplifying economic and life safety risks.

The great danger of hazard cascades is that they remain unrecognized. Imagining and quantifying the interacting chain of processes requires highly specialized skills. The hazard process-chains may be immediate (e.g., a rock avalanche evolving into a debris flow, which, in turn, dams a receiving stream), delayed by weeks or months (e.g., a large Landslide choking a receiving river with sediment leading to downstream river-bed aggradation), or delayed by many years, decades, or even centuries (e.g., a Landslide dam causing upstream flooding and complete fluvial regime change). See Appendix F: Evolving Practice, subsection F.6 Hazard Chains for examples.

QPs are required to identify hazard chains for any level of effort (Appendix B) that can reach the area of interest. This requires the QP to examine hazards both upstream (e.g., remote source Landslide, outburst flood) and downstream (e.g., retrogressive Landslide, Landslide damming).

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[8] The black swan theory refers to unexpected or surprise events of large magnitude and Consequence. The theory was developed to explain:

- the disproportionate role of high-profile, hard-to-predict, and rare events that are beyond the realm of normal expectation;
- the non-computability of the probability of the consequential rare events using scientific methods (owing to the very nature of small probabilities); and
- the psychological biases that blind people, both individually and collectively, to uncertainty and to a rare event's massive role in historical affairs.

3.3.2.7 Runout Analysis

For Landslide Assessments, the QP must estimate the chance of a Landslide reaching the proposed or existing development. This can be accomplished empirically or numerically. Many methods exist, and the QP will need to research and determine which method is most suited for the objective of a study. To this end, review papers are particularly helpful (e.g., McDougall 2017). Detailed mapping of the runout of previous events remains a viable alternative if it can be done at a sufficient degree of completeness.

The choice of which analytical method to use depends on various factors including the level of effort required by the assessment (e.g., empirical versus numerical); and the Landslide type(s) expected. Appendix C: Review of Levels of Landslide Safety provides information on when numerical modelling is advisable. With class 2 and 3 assessments, with multiple potential life loss or high economic losses, use of more than one model is encouraged, with model calibration whenever possible to ascertain the most realistic outcome.

Numerical models should not be blindly relied on, and the QP should always compare runout results with field evidence to avoid model misuse. Where an existing or proposed development may be within reach of potential runout, and where uncertainty is high, structural mitigation or avoidance may be effective mitigation measures to cope with uncertainty.

3.3.2.8 Compilation of Landslide Hazard Maps

In many cases, Approving Authorities will base land-use decisions and development approvals on Landslide Hazard maps. The QP is responsible for determining if those maps exist; if they do, the maps will form the basis for a QP's assessment. If the maps are not at a scale that the QP can readily use for a site-specific assessment, the QP will need to develop a hazard map (see Appendix F: Evolving Practice, subsection F.8 Landslide Hazard Mapping).

Currently, in Canada, there is no consistent method for presenting Landslide Hazards. However, at the very least, maps must meet basic cartographic standards (e.g., appropriate scale, locational grid, legend, labelling). The fact that there is no such unified system to portray hazard intensity (e.g., frequency, intensity indices, colour code schema) means that hazard maps within a province or even within a Regional District or Municipality may look very different in terms of what the hazard maps show. Differences of information visualization in various hazard maps increase the chances for misinterpretation of the information and decrease the ability for comparison between different map types.

Appendix F: Evolving Practice, subsection F.8 Landslide Hazard Mapping provides a brief history of Landslide Hazard map development in BC and includes some initial guidance towards a unified system. QPs may wish to consider following this guidance, so their work can be compared to other work elsewhere.

3.3.3 SLOPE STABILITY ANALYSIS

Most Landslide Assessments are carried out for individual properties or small developments that are in direct contact with and affect steep slopes. Determination of the slope hazard with potential to impact the development may not be relevant, as the stability could be conditioned by onsite anthropogenic impacts resulting from the development proposal. These cases may demand the Landslide Hazard be estimated by determination of the Factor of Safety (FS) of the slope.

Analysis of soil slopes fall under two primary categories:

- stability analysis of slopes that rely on adequate information to model subsurface conditions (drained/undrained soil strengths, drained/undrained conditions and water pressures); and
- deformation analysis of slopes that require adequate information about stress-strain behavior of soils incorporated in the slope model.

Slope stability analysis using a limit equilibrium method is the typical approach to evaluate driving and resisting forces acting on soil slices along a discrete critical sliding surface within the developed soil slope model. Limit equilibrium methods are typically used for slope stability analysis, as they provide a relatively simple approach for direct measurement of stability calculated as an FS required for slope equilibrium.

Deformation analysis of slopes using the finite element method is used to evaluate stresses and movements in slopes. Finite element analyses require specialized expertise and substantial design effort to develop a soil model that provides a reasonable representation of actual behavior of the selected soil slope.

3.3.3.1 Subsurface Exploration Plan

Subsurface exploration efforts should be designed to resolve uncertainties revealed during surface observation and mapping efforts. The site exploration plan should be based on an understanding of:

- Quaternary geology;
- surface expression;
- site access;
- anticipated or inferred geological and hydrogeological conditions to define the plan area of the exploration;
- exploration method(s);
- test locations and depths;
- in-situ testing methods;
- instrumentation requirements; and
- sampling types and frequencies and Landslide type.

Site exploration plans should consider the potential for encountering artesian or flowing artesian conditions at test-hole locations, and should consider methods for adequately sealing test holes that encounter this groundwater condition. Guidance for groundwater management for exploration boreholes is provided in the *Groundwater Protection Regulation: Guidance Manual* (BC Ministry of Environment and Climate Change Strategy 2019).

3.3.3.2 Exploration, Testing, and Instrumentation

Site exploration methods can range from reconnaissance methods to extensive site excavation and field-testing methods, depending on study slope complexity. For most property-scale assessments, site-exploration methods involve the following site-exploration efforts:

- Site reconnaissance mapping and exploration using sounding probes, portable augers and samplers, shallow test pits and trenches, and penetration tests. Site reconnaissance exploration is carried out to limited depth and is not typically carried out to characterize slopes for deep-seated instability.
- Site exploration using drilling equipment, soil sample extractors, in-situ penetration tests (physical and electric), in-situ soil strength tests, downhole geophysical measurements, and piezometer installation and measurement.

For guidance on the type of information to be collected, see Appendix B: Landslide Assessment – Determining the Level of Effort, subsection B.2.4 Level of Effort Tables B-1 to B-5, and/or Appendix E: Methods of Seismic Analysis of Soil Slopes, subsection E.5 Liquefaction Displacement Assessments.

Groundwater is a common cause or trigger of slope instabilities. Identification and detection of groundwater conditions should be considered critical components of site-exploration efforts, and the QP should take steps to obtain any groundwater information from local jurisdictions or stakeholders.

Groundwater condition determinations for a study slope should include, but may not be limited to, the following considerations:

- Onsite and offsite surface water channels and ponded surface water areas
- Disturbed or cleared slope surfaces
- Slope seepage
- Slope condition during seasonally wet weather conditions
- Soil permeabilities encountered during test hole exploration
- Piezometric data with consideration of seasonal fluctuations

In any case, the QP must justify and document the choice of variables based on in-situ measurements.

3.3.3.3 Limit Equilibrium Analysis and Factor of Safety

Estimation of the Factor of Safety (FS) of a slope (static and seismic) and slope displacement (seismic) are quantitative (deterministic) analysis methods that may be selected by the QP to estimate Landslide Hazard.

These estimates of Landslide Hazard are typically selected for non-active slopes where the geology of the area is well understood, and where there is sufficient site exploration information available to characterize subsurface conditions of the study slope. Active slopes (i.e., slow-moving Landslides) have an FS of approximately 1.0 (or marginally less) such that estimates of Landslide Hazard using limit equilibrium analysis may involve analysis of FS sensitivity to changes in slope geometry, groundwater conditions, or Landslide shear strength being used to inform the hazard.

Minimum acceptable FS data are presented in the current *BC Building Code* reference documents, the BC Ministry of Transportation and Infrastructure *Supplement to the Canadian Highway Bridge Design Code, S6-14* (BC MOTI 2016), and the *Canadian Foundation Engineering Manual, 4th Edition* (Canadian Geotechnical Society 2006). Generally, for low-Consequence and/or temporary slopes in static condition, the FS should be at least 1.3. For slopes that support or that may directly impact buildings, a minimum static FS of 1.5 is recommended. Other considerations that may impact the adoption of an appropriate FS include model and parameter uncertainty, and potential for progressive slope failure.

The QP needs to consider the following key items in assessing the stability of slopes using limit equilibrium methods:

- The level of effort applied to the site investigation, the slope stability model, and parameter uncertainty
- The potential Consequences of slope failure
- Slope geometry and geological controlling factors
- Shear strength of the soil or rock, and the potential for a loss of strength if the slope deforms
- Semi-static water levels, pore pressures, or seepage forces
- External loading and environmental conditions

Slope geometry and hydrogeological/geological conditions tend to be the controlling factors in the form of discrete surface slope movements. Basic forms of discrete surface slope movements comprise translational, planar/wedge, and circular/non-circular rotational displacements (or any combination of these).

Onsite slopes that do not meet minimum FS requirements typically include additional analysis that incorporate theoretical stabilization measures in the slope analysis (for example sub-drains, slope flattening, retaining walls/buttresses) to assess potential for study slope to achieve a suitable FS. Study site slopes in developed areas may not necessarily be able to implement stabilizing measures in development designs due to costs or property constraints. For these cases, mitigation measures typically comprise determination of slope setbacks to avoid the hazard. In some cases, the stability analysis findings may determine the slope (and influence areas) unsafe for the use intended.

3.3.3.4 Seismic Slope Analysis

Earthquakes can destabilize slopes leading to Landslides; cause liquefaction leading to Landslides or flow slides; and/or cause slope displacements.

The diagram in Figure 4 provides general guidance on selection of the appropriate type(s) of seismic slope analysis, to anticipate Landslides that may result from earthquake events.

The seismic slope stability flowchart assumes the Landslide Hazard or Landslide Risk analysis has been completed and the geological model for the slope is considered suitable for seismic slope stability analysis.

The initial step (outlined in bold in Figure 4) consists of an assessment of liquefaction or strain-softening potential of slope soils. If liquefaction or strain-softening potential is considered likely, then Flow Path 1 should be followed. Procedures to estimate the potential for, and Consequences of, liquefaction are referenced in Appendix E: Methods of Seismic Analysis of Soil Slopes.

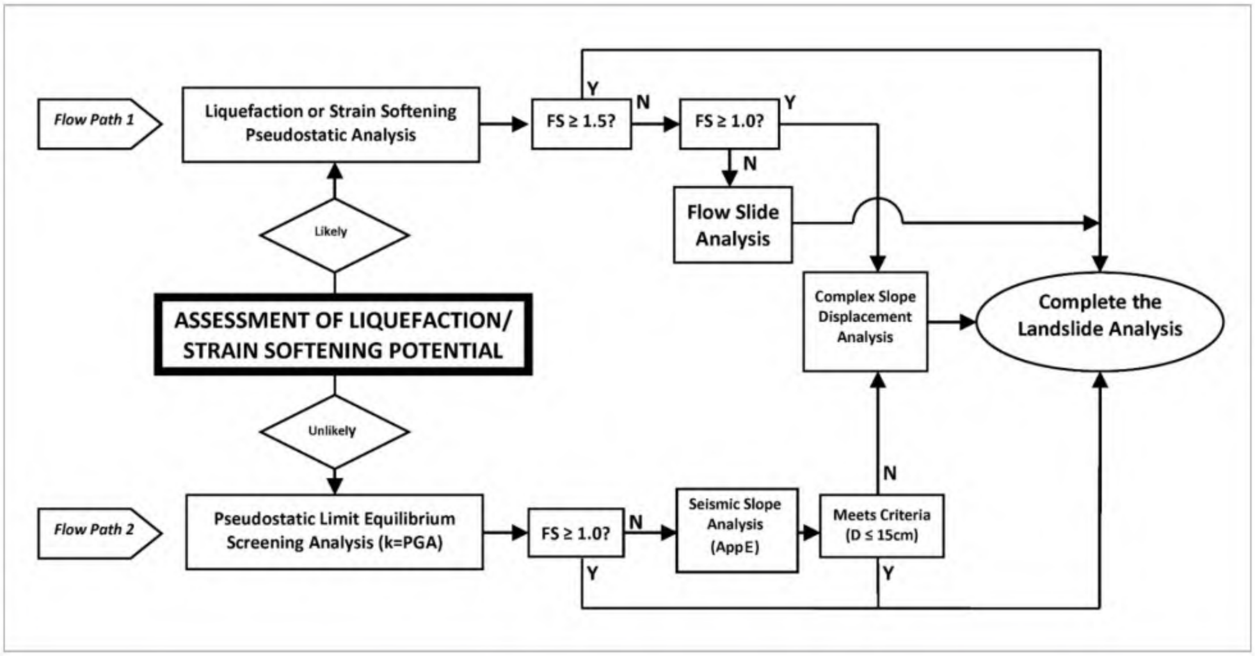

Figure 4: Flowchart showing the process for seismic slope stability analysis

NOTES: Abbreviations: FS = Factor of Safety; PGA = peak ground acceleration

If liquefaction or strain-softening potential is considered unlikely, then Flow Path 2 should be followed. The initial step of Flow Path 2 screens the slope using a seismic coefficient equal to the peak ground acceleration (PGA) of the design earthquake (2% probability of exceedance in 50 years). If the resulting FS is greater than or equal to 1.0, no additional seismic slope analysis is warranted. But if the resulting FS is less than 1.0, then the procedures to estimate seismic slope displacement in Appendix E: Methods of Seismic Analysis of Soil Slopes should be followed

Advancement of the historical Newmark-type sliding block model to evaluate seismic performance of natural slopes developed by Bray and Travasarou (2007), and included in the previous version of these guidelines, utilized the 4th generation Ground Motion model (from the *National Building Code of Canada [NBC] 2005*). The *BC Building Code 2018* has adopted the 5th generation Ground Motion model (from the *NBC 2015*) that developed a probabilistic treatment of the Cascadia subduction earthquake such that seismic hazard calculations are now fully probabilistic.

Current practice involves determination of a pseudostatic coefficient that represents a fraction of the PGA such that slope equilibrium is achieved (i.e., FS = 1.0). Procedures have been developed that include consideration of an allowable seismically induced displacement (D) for the slope system. As a guideline, D equal to 15 cm or less is considered tolerable with respect to life safety, as described in the Structural Commentaries to the *NBC 2015*.

The tolerable slope displacement of 15 cm is proposed as a guideline, based on experience with residential wood-frame Construction. These guidelines are not intended to preclude a QP or an Approving Authority from selecting another appropriate value. The QP should strive for a balance between the location of the proposed building and the associated seismic slope displacement.

The estimation of the pseudostatic coefficient only considers a single intensity measure such as spectral acceleration or PGA. As such, contributions to the displacement hazard from different tectonic environments (or displacement models) are not necessarily represented (i.e., shallow crustal, interface, and intraslab zones).

A probabilistic method developed by Wu (2017) provides a rational approach for combining seismic slope displacements using hazard spectra for crustal, inslab, and interface sources published by Halchuk et al. (2016). This approach is discussed in further detail in Appendix E: Methods of Seismic Analysis of Soil Slopes.

3.3.3.5 Complex Slope Displacement Analysis

Slope soils may be encountered that are considered likely to liquefy or undergo strain-softening behaviour or may warrant complex slope displacement determinations (see Figure 4, Flow Path 1 above).

Such instances include, but are not limited to:

- slopes that do not meet the 15 cm slope displacement criteria;
- slopes composed of very soft or sensitive clay or silt soils;
- slopes where soil-structure interaction analysis may allow slope displacements greater than 15 cm; or
- slopes where an estimate of Landslide runout at the base of the slope is required.

Complex slope displacement analysis typically requires specialized knowledge described in Section 3.5 Landslide Hazard or Risk Reduction – Speciality Services of these guidelines.

3.3.4 WEIGHING TYPES OF RISK ASSESSMENT

Risk is a measure of the probability and severity of an adverse effect to health, property, or the environment, and is estimated by the product of hazard probability and Consequences (Australian Geomechanics Society 2007).

For Landslide Risk assessment, the typical components may be outlined according to the guidance in Appendix F: Evolving Practice, subsection F.2 Quantitative Risk Assessments.

3.3.4.1 Partial Risk or Encounter Probability Approaches versus Quantitative Risk Assessment

Hazard-based partial risk or encounter probability approaches use Landslide intensities associated with specific hazard return periods affecting the site to inform the management response, which may include avoidance, protective measures, Covenants, or development without constraint.

Except in a generalized, categorical way (i.e., new build versus subdivision; damaging versus lethal), hazard-based approaches typically do not include an assessment of the potential temporal exposure or vulnerability (i.e., the Consequences) associated with the hazard, and therefore implicitly assume society's risk tolerance. This approach has been applied in BC for many years (Cave 1993).

The weakness of the approach is illustrated by this example: It may not be justified to protect an infrequently used vacation cottage from Landslides to the same degree as, for example, a high-density apartment complex or a new subdivision with critical infrastructure (e.g., hospital, firehall, police station).

A hazard-based approach with fixed return periods does not allow for such comparison, as it is insensitive to the potential Consequences. Fund allocation towards the highest hazard sites can miss sites with high loss potential. Or, by ignoring Consequences, application of the hazard-based approach can lead to over- or under-design of mitigation measures. It can, however, be used as a first step to identify the need for a follow-up risk assessment. In some circumstances, Local Government policy documents or risk management approaches may also incorporate a hazard-based approach into a semiquantitative risk analysis framework.

In contrast, quantitative risk assessments aim to provide numerical values for risk of loss of life and, sometimes, for risk of economic losses. This is achieved by multiplying the probability of a Landslide by the chance of an infrastructure (e.g., a house) being impacted by the potential Landslide, the occupancy (time spent) of people inside the house (for life loss), the vulnerability of the people (their chance of dying given the impact), and the number of people potentially exposed. For economic risk assessments, the damage or replacement value is considered. Importantly, the life-loss or economic damages are integrated across the entire probability spectrum being considered and can be annualized for easier comparison.

This risk-based approach avoids the pitfalls of the hazard-based approach, by including Consequences in the calculations and thus requiring a different standard of mitigation for facilities with higher Consequences. Therefore, different sites can be compared by risk, and funds can be allocated logically towards the highest risk sites. Finally, the risk-based approach is suitable for cost-benefit analysis of mitigation measures and rational selection of the appropriate degree of protection.

For higher level-of-effort quantitative assessments (see Appendix B: Landslide Assessment – Determining the Level of Effort), estimation of the Consequences within the entire consultation zone requires a significant level of effort. Appendix F, subsection F.2 Quantitative Risk Assessments provides details on the use of quantitative methods for Landslide Risk assessments.

3.3.4.2 Quantitative versus Qualitative Estimates

Quantitative estimates use numerical values or ranges of values, while qualitative estimates use relative terms such as high, moderate, and low. Quantitative estimates are typically based on objective (statistical or mathematical) estimates, while qualitative estimates are mostly based on subjective (professional judgmental or assumptive) estimates. No standard definitions exist for relative qualitative terms. Therefore, to avoid ambiguity, such terms must be defined with reference to quantitative values or ranges of values.

Quantitative estimates may be no more accurate than qualitative estimates. The accuracy of an estimate does not depend on the use of numbers. Rather, it depends on whether the components of the Landslide analyses have been appropriately considered, and on the availability, quality, and reliability of data being relied on.

Anthropogenic impacts on natural Landslide frequency can be captured in quantitative estimates; for example, by changing the frequency of Landslides $P(H_i)$, should there have been an alteration in an upslope watershed (e.g., presence of legacy forest roads) or the Landslide itself. The magnitude of the change will often be difficult to estimate, in which case a sensitivity study may help to constrain the uncertainties.

The decision whether to carry out and report the results of a Landslide analysis quantitatively or qualitatively also depends on other considerations: the level of effort required, the data availability, how the adopted Level of Landslide Safety is expressed, and/or the requirements of the Approving Authority.

3.3.4.3 Semi-quantitative Risk Assessments

Semi-quantitative risk assessment involves the same steps as quantitative risk assessment, with the difference that hazards and Consequences are combined in a qualitative matrix to arrive at a risk classification ranging from very low to very high.

Figure 5: Example of a semi-quantitative risk matrix for geohazard risk assessments shows an example risk evaluation matrix used to combine likelihood of unwanted outcome (left column) and Consequence assessment (lowermost six rows) to determine a risk rating for debris flood/flood hazards (coloured centre portion).

The probability of the undesirable outcome and the severity of the Consequence defines an intersection point in the matrix that ranks the risk scenario from “Very Low” to “Very High.” The risk ranking of all categories can then be used to prioritize risks for comparison of potential risk reduction measures.

RISK EVALUATION AND RESPONSE		
VH	Very High	Risk is imminent and could happen at any time irrespective of particular triggers; short-term Risk reduction required; long-term Risk reduction plan must be developed and implemented
H	High	Risk is unacceptable; long-term Risk reduction plan must be developed and implemented in a reasonable time frame; planning should begin immediately
M	Moderate	Risk may be tolerable; more detailed review required; reduce Risk to ALARP[a]
L	Low	Risk is tolerable; continue to monitor and reduce risk to ALARP[a]
VL	Very Low	Risk is broadly acceptable; no further review or Risk reduction required

LIKELIHOOD OF UNDESIRABLE OUTCOME $P_H \times P_{S|H}$

LIKELIHOOD DESCRIPTIONS	PROBABILITY RANGE	1 Negligible	2 Minor	3 Moderate	4 Major	5 Severe	6 Catastrophic
Event can be expected at least once per year	>0.9	M	H	H	VH	VH	VH
Event typically occurs every few years	0.1 to 0.9	L	M	H	H	VH	VH
Event possible within the lifetime of a temporary facility	0.01 to 0.1	L	L	M	H	H	VH
Event unlikely within the lifetime of a temporary facility	0.001 to 0.01	VL	L	L	M	H	H
Event very unlikely within the lifetime of a temporary facility	0.0001 to 0.001	VL	VL	L	L	M	H
Event is extremely unlikely within the lifetime of a temporary facility	<0.0001	VL	VL	VL	L	L	M

CONSEQUENCE DESCRIPTIONS AND INDICES

INDICES	1 Negligible	2 Minor	3 Moderate	4 Major	5 Severe	6 Catastrophic
SAFETY	Minor workforce injury; no public impact	Workforce lost-time accident; no public impact	Workforce long-term disability; minor public injury	Workforce fatality; serious public injury	Multiple workforce fatalities (<10); public fatality	Multiple workforce fatalities (>10); multiple public fatalities
ENVIRONMENT	Insignificant	Localized short-term impact; recovery within days or weeks	Localized long-term impact; recoverable within the lifetime of the project	Widespread long-term impact; recoverable within the lifetime of the project	Widespread impact; not recoverable within the lifetime of the project	Loss of a significant portion of a valued species
ECONOMIC	Negligible; no business interruption; <$10,000	Some asset loss; minimal business interruption <$100,000	Serious asset loss; up to 1 day business interruption; <$1 million	Major asset loss; up to 1 week business interruption; <$10 million	Severe asset loss; up to 1 month business interruption; <$100 million	Total loss of asset; >1 month business interruption; >$100 million
REPUTATION	Negligible impact	Slight impact; recoverable within days	Local publicity; recoverable within weeks	National publicity; temporary (weeks to months) loss of market share	International publicity; long-term (years) loss of market share	May threaten corporation's survival

Figure 5: Example of a semi-quantitative risk matrix for geohazard risk assessments

NOTES:

[a] ALARP stands for "as low as reasonably practicable"

The risk matrix provided in Figure 5 is also known as multi-criteria analysis (MCA). Relative to a cost-benefit analysis (CBA), the main merit of MCA is that it explicitly considers project impacts that are not easily assigned monetary values, and which are often referred to as "intangibles" in CBA. Therefore, MCA can account for social, cultural, and environmental impacts of flood risk-reduction projects.

In addition, MCA facilitates stakeholder involvement, and thus renders the appraisal and decision-making process more transparent. A drawback of this method is that the Consequence ratings for some categories are subjective, and responses can vary greatly between individuals. This figure can and should be altered by QPs, Clients, or Approving Authorities to fit their specific needs.

It is well within an Qualified Professional's capability to estimate safety risks. However, economic and environmental risks may require specialist input. Similarly, social, cultural, and intangible (such as human stress) risk should typically be evaluated by others, such as social scientists, local populations, and affected First Nations, where applicable.

If such Consequence aspects are relevant, the QP should consult with the Client and the Approving Authority to clarify how those Consequences should be evaluated.

3.3.5 CHANGED CONDITIONS AND CLIMATE CHANGE EFFECTS

Landslide analysis requires consideration of changes to existing conditions, including:

- changes to slope geometry from either natural geomorphic processes or human activities;
- changes in land use and/or changes resulting from resource or urban development;
- changes caused by natural processes such as earthquakes and volcanic eruptions;
- effects of rising sea level on foreshore slopes and beach erosion;
- changes to surface and/or subsurface flow patterns from either natural change in precipitation trends and runoff patterns, or from land use (e.g., road networks, storm drainage);
- effects of wildfires and insect infestations on vegetated slopes; and
- anthropogenic climate change effects on hydrogeomorphic conditions, fire frequency, and insect infestation.

Some of the bullets above involve specialized assessments. In cases where QPs are not experienced with the required subject matter, specialists or other experts should be consulted.

Anthropogenic climate change is becoming a major agent of geomorphic process change globally. Its inclusion, whether qualitatively or quantitatively, is required, as past conditions are increasingly an unreliable proxy for future conditions. The field of climate change effects on Landslides is vast and complex (Jakob 2022) and no all-encompassing guidance can be provided, as each Landslide type will behave differently according to the effects of climate change. Further discussion of these aspects is provided in Appendix F: Evolving Practice, subsection F.5 Landslides and Climate Change.

However, despite these considerations, the following general steps for including climate change considerations in Landslide Assessments remain the same:

1. Isolate the causes and triggering mechanisms of the Landslide type in question.
2. Determine which of the causes and triggers are associated directly or indirectly with climate change.
3. Provide, where possible, a quantitative response model of the hydroclimatic trigger (or Landslide movement accelerator).

4. Search for the most complete local climate change predictions (i.e., as applicable, temperature, long-term precipitation, high-intensity precipitation, changes in snowpack, streamflow).
5. Select one or more emission scenarios and apply the projected changes to the Landslide response model.
6. Report the results for one or more timeframes in question (e.g., mid- to late-century or beyond).
   - The Pacific Climate Impacts Consortium (PCIC) online tools provide much of the information requested in items 4 to 6 above (pacificclimate.org/analysis-tools; PCIC 2022). However, in some cases other model ensembles may need to be consulted to reduce climate uncertainties. This will only be required for particularly climate-sensitive cases.
   - QPs should consult with the Client or Approving Officer to determine appropriate timeframes, which may or may not hinge on the design life of a proposed structure, especially given that most Residential Developments will continue to exist in perpetuity.
   - For Residential Developments, end-of-century scenarios should be the minimum. Most climate models do not provide data beyond the end of the century, largely due to the greatly enhanced uncertainty associated with the materialization of emission reductions.
7. Attempt to quantify uncertainties, where possible.

Additional guidance on how to include climate change considerations in Landslide Assessments is provided in Appendix F: Evolving Practice, which provides a systematic summary of the effects of climate change on various Landslide processes (Jakob 2022). This could be a starting point to examine the sensitivity of a Landslide to climate change. The depth and breadth of the effects analysis of climate change on Landslides should be contingent on a preliminary assessment of Landslide vulnerability to climate change and the Landslide Consequences.

3.3.6 LANDSLIDE ASSESSMENT REPORT

The QP provides the results of the Landslide Assessment to the Client in a written report, which, along with the Landslide Assessment Assurance Statement, is submitted to the Approving Authority.

Report formats will vary depending on the study objective, the type of Landslide Hazard or Landslide Risk analysis, and the required level of effort. If they exist, the QP should follow guidelines issued by the Approving Authority for preparing the Landslide Assessment Report.

The QP should consider reviewing the format and contents of the Landslide Assessment Report with the Client and the Approving Authority prior to finalizing the report.

Most Landslide Assessment Reports are done at a feasibility level of a project. This means that reports identify and characterize hazards and risk, but typically do not include sufficient detail to move directly to engineering and Construction of mitigative works, should those be required. Engineering studies suitable for Construction of mitigation works typically require a separate scope of work.

Typically, a Landslide Assessment Report should include:

- a description of the development;
- the legal description of the property;
- a location map or description of the site and study area relative to well-known geographic features;
- the site plan of the property including topography, natural features, logging activity, existing structures, roads, infrastructure, existing surface drainage, proposed surface water alterations, dry wells, and stormwater storage ponds;
- a terrain map or physical description of the study area;
- the objectives of the study, method of Landslide Hazard or Landslide Risk analysis, and level of effort;

- a list of background information available, collected, and reviewed, and its relevance;
- identification of the type of Landslide Hazards affecting the site;
- observed or inferred Landslide movement rates determined from on-site measurements, or from air photographs, still photo photogrammetry, or LiDAR change-detection techniques;
- methods and intensity of fieldwork;
- observations of topography, geology, Landslide processes, and Elements at Risk;
- if applicable, the adopted Level of Landslide Safety used for comparison;
- the results of the Landslide Assessment;
- conclusions, accompanied by supporting rationale;
- an estimate of the associated residual risks if the recommendations are implemented;
- if required, recommendations for further work and requirements for future inspections, and by whom the work will be conducted;
- recommendations, if requested and as required, to reduce the Landslide Hazards and/or Landslide Risks;
- definitions of qualitative terms, technical terms, concepts, and variables;
- other information as specified in the Agreement with the Client, or as required in jurisdictional guidelines;
- references, including maps and air photos; and
- limitations and qualifications of the assessment and report, assumptions, error limits, and uncertainties.

8. Reports should be accompanied by drawings, figures, sketches, photographs, test hole or test pit logs, laboratory test results, tables, and/or other support. information such as digital files (see Appendix F: Evolving Practice, subsection F.3 Digital Deliverables), as required. Graphic information should be consistent with the information in the text. Maps or plans should delineate the areas of Landslide Hazard and Landslide Risk in relation to existing and proposed development.

For Landslide Assessments relating to a Covenant, the QP should consider including a section in the report that clearly lists the restrictions that should be included in the Covenant. In some cases, those restrictions are written into the Covenant, rather than appending the report to the Covenant.

The report should be clearly written with sufficient detail to allow the Client, Approving Authority, and others reviewing the report to understand the methods, information used, and supporting rationale for conclusions and recommendations, so they can decide on approvals without necessarily visiting the property or site. Landslide Assessment Reports are frequently included as part of a Covenant on a property's title, and convey important information to existing and future owners of the land; therefore, reports should be readable, free of excessive jargon, and provide conclusions and recommendations that are understandable to the lay person.

An independent review of the Landslide Assessment Report, prior to its submission to the Client and Approving Authority, is often required as part of the quality assurance/quality control program (see Section 4.1.7 Documented Independent Review of High-Risk Professional Activities or Work). Independent review of work that is considered high risk (which most Landslides assessments are) is also a requirement in the Engineers and Geoscientists BC Bylaws, Section 7.3.6.

3.4 UNCERTAINTIES, LIMITATIONS, AND QUALIFICATIONS OF A LANDSLIDE ASSESSMENT

Uncertainties, limitations, and qualifications of a Landslide Assessment should be described clearly in the Landslide Assessment Report.

3.4.1 DETERMINING LIMITATIONS AND QUALIFICATIONS

The limitations and qualifications of a Landslide Assessment depend on multiple factors:

- Objectives of the study
- Method(s) of Landslide Hazard or Landslide Risk analysis
- Level of effort
- Size of the study area
- Stability and geological and geotechnical complexity of the terrain
- Type of development
- Elements at Risk
- Availability, quality, and reliability of background information and field data
- Intensity of fieldwork
- Technical and local experience of the QP
- Whether or not a defined Level of Landslide Safety has been adopted by the approving jurisdiction

Although fieldwork associated with a Landslide Assessment can provide reasonable coverage of the study area, fieldwork may not encompass the entire study area, or all areas potentially affected by the development. The extent of fieldwork should be described in the report.

Many aspects of a Landslide Assessment are qualitative and subjective, based on observed, inferred, and assumed conditions informed by the accumulated experience of the QP. All assumptions must be clearly identified and all issues that have not been addressed in the assessment should be highlighted.

Only some Landslide Assessments include subsurface investigations, sampling, instrumentation, monitoring, and laboratory testing. Where hazard assessment has required expert judgment, hazard frequencies are considered shorter, and uncertainty is significant, then discussion of residual risk is warranted.

A Landslide Assessment cannot be relied on in perpetuity; however, the QP should make efforts to provide a Landslide Assessment that is not sensitive to short-term variabilities that might affect its conclusions within the timeframe of its intended use. Although both the Client and the QP should attempt to anticipate reasonable changes in the future that could affect the results of the Landslide Assessment, the validity of a Landslide Assessment Report over time depends on multiple factors, such as:

- the occurrence of subsequent Landslides;
- changes in land use at and upslope of the property;
- drainage alterations;
- other types of site developments;
- Landowner neglect;
- the discovery of previously unknown information; and
- hydrogeomorphic changes related to climate change.

In some cases, development permit applications, especially for larger subdivisions, may take years to complete. It is the Landowner's responsibility to procure a Landslide Assessment that is of sufficient scope to address the requirements its intended use, and that accounts for foreseeable site variabilities such that the report does not become obsolete within the timeframe of its intended use.

3.4.2 IDENTIFYING UNCERTAINTY

Uncertainty is an inherent part of Landslide Hazard and Landslide Risk assessments. It is intrinsic in data collection, analysis, assessment, and decision making (Morgan et al 1990; Vick 2002). This necessitates that uncertainty be identified, reduced when practical, clearly communicated, and accommodated.

The following elaborates on uncertainties inherent in Landslide Hazard and Landslide Risk assessments. This content is largely summarized from the *Technical*

Aspects of Snow Avalanche Risk Management–Resources and Guidelines for Avalanche Practitioners in Canada (Canadian Avalanche Association 2016) and modified to reflect uncertainty for Landslide Hazard and Landslide Risk assessments.

See also Appendix G: Strategies for Uncertainty Reduction.

3.4.2.1 Types of Uncertainty

Uncertainty is defined as the state, even a partial state, of deficiency of information related to the understanding or knowledge of an event, and its Consequence or likelihood (per ISO 31000:2018, Risk Management – Guidelines).

Uncertainty can be subdivided into three categories: natural (aleatoric), knowledge-source (epistemic), and analysis uncertainty:

- **Natural uncertainty**:
  - Inherent to a system due to natural variability or randomness (e.g., the difference in causes and triggers of Landslides)
  - Cannot be reduced, due to random variability such as rainfall or snowmelt volumes and rates
  - Should be considered in Landslide Assessments
- **Knowledge-source uncertainty**:
  - Arises from limited information or understanding about a model or process, limits on the accumulated experience of the assessor, and limitations of the underlying data
  - These factors affect the definition of the credible hazard, and any sources of uncertainty should be communicated to the risk owner
  - Can be reduced, although the benefit in doing so varies based on the level of effort (see Appendix B: Landslide Assessment – Determining the Level of Effort)
- **Analysis uncertainty**:
  - Arises when slope stability analysis using the limit equilibrium analysis method involves discretizing a sliding mass into slices to evaluate interslice forces to determine normal stress along a critical sliding surface
  - Satisfies statics but does not consider strain/displacement relationships, and thus solves for the condition of all forces in the slide mass acting at the same time (i.e., Factor of Safety is the same for each slice)
  - Iteration of a closed limit equilibrium analysis may achieve mathematical convergence at the expense of non-representative interslice and slip surface forces (line of thrust outside slide mass and divergence between slices)

3.4.2.2 Sources of Uncertainty

Uncertainty in Landslide Hazard and Landslide Risk assessment and mitigation arises from a variety of internal and external sources, including the following:

- **Weather and Climate**:
  - Forecasted weather, which involves uncertainty, can be the basis for Landslide prediction.
  - Changes in climate are altering the causative factors and triggers of Landslides (Friele et al. 2020; Jakob 2022; Sobie 2020; Jakob and Owen 2021).
- **People**:
  - Human behaviour generates uncertainty; for example, individuals may be in unexpected places at the time of a Landslide, or they may be attracted to an ongoing Landslide event that brings them into closer proximity.
  - People's perception of the relevant environmental factors, including terrain, their assessment of the conditions, and subsequent actions, are all sources of uncertainty.
  - Sources of uncertainty often stem from unknown water management practices, excavations, and fill placements.

- Terrain:
  - At any point in time, terrain can be considered constant with no associated uncertainty.
  - However, over time terrain can be modified by activities and events such as road development, logging, fire, slope mass movement, glacial ablation or advance, Construction projects, and mining.
- Time:
  - Deterministic slope stability analysis will eventually expire and become invalid.
  - These estimates typically reflect an evaluation of the slope conditions at the specific point in time of the analysis (i.e., baseline analysis) and may not be an accurate representation of slope conditions over the long term (Popescu 1994).

Artificial and natural processes such as those illustrated in Figure 6 can negatively impact the stability of slopes and/or promote erosion, adding to uncertainty, so the QP should consider such processes in the Landslide Assessment.

Artificial processes with potential to negatively impact the stability of slopes include, but may not be limited to:

- excavations into the slope or slope toe areas;
- water leakage from onsite and/or offsite water lines, storm lines, and sanitary sewer lines;
- groundwater changes from roof waters, dry wells, rock pits, and other stormwater systems introduced by zoning bylaws requiring infiltration systems to modulate storm flows;
- excessive vibration from heavy machinery, such as compaction equipment or pile drivers;

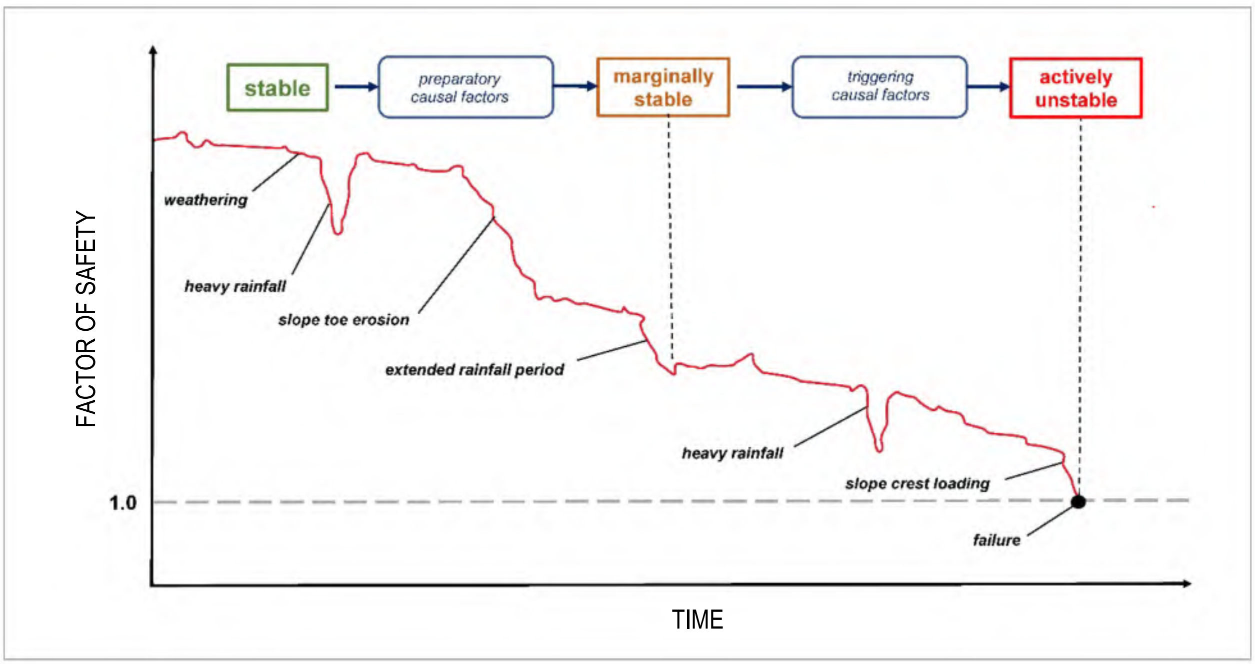

Figure 6: Illustration of changes in slope stability Factor of Safety over time

NOTES:

Figure adapted from Popescu (1994). The preparatory causal factor makes the slope susceptible to movement (i.e., tends to move the slope towards a condition of marginal stability). The triggering causal factor initiates slope movement (i.e., tends to move the slope from marginally stable towards a condition of active instability).

- defective maintenance of slope drainage systems;
- loading of slopes and/or slope crests (e.g., by fill or structures);
- excessive landscape watering;
- construction of ponds, pools, or other water-retention structures with potential for uncontrolled leakage;
- removal of trees and vegetation from onsite and/or offsite areas; and/or
- unexpected changes to groundwater flow regimes due to site development.

Natural processes with potential to negatively impact the stability of the steep site slopes include, but may not be limited to:

- extended periods of seasonally wet weather;
- storm events with exceptionally high rainfall intensity and duration;
- earthquakes;
- removal of slope tree and vegetation cover by disease or fire;
- stream erosion; and/or
- localized instabilities impacting overall slope loading.

3.5 LANDSLIDE HAZARD OR RISK REDUCTION – SPECIALTY SERVICES

QPs must confirm that they have appropriate training and experience to design and execute a Landslide Assessment associated with the complexity of the project terrain and geology and, if not, involve required specialists. A QP must be able to determine areas where their training and experience is limited and should refer tasks within those areas to others whose experience is more specific to the task.

Specialty services are tasks for which a QP may not have the required training and experience. Note in particular the different skill sets of Geoscience Professionals and Engineering Professionals; each professional may be suited to a specific task in a Landslide Assessment.

The Client should not expect one QP to provide all services, and should anticipate that diverse specialties may be required in a Landslide Assessment. This should be clear in the Agreement between the QP and the Client. A QP may be needed to coordinate Landslide Assessments where multiple specialists are required.

For some Landslide Assessments, the following specialty services may be required:

- Slope deformation analyses using numerical methods
- Surface or subsurface monitoring equipment installation and monitoring
- Numerical Landslide runout modelling
- Hydraulic discharge modelling
- Landslide magnitude/frequency analysis and modelling
- Change detection from photogrammetry, satellite images (e.g., InSAR), or LiDAR
- Investigation, option analysis, and design of slope stabilization and/or structural protection works including surface water and stormwater mitigation systems
- Subsurface drainage design, especially with respect to potential impacts on slope stability

During the course of the Landslide Assessment, if the QP identifies a need for specialty services, the QP should notify their Client. The QP must then either revise the scope of work or recommend another QP to carry out the specialty service or services.

4.0 QUALITY MANAGEMENT IN PROFESSIONAL PRACTICE

4.1 ENGINEERS AND GEOSCIENTISTS BC QUALITY MANAGEMENT REQUIREMENTS

Engineering/Geoscience Professionals must adhere to applicable quality management requirements during all phases of the work, in accordance with the Engineers and Geoscientists BC Bylaws and quality management standards.

To meet the intent of the quality management requirements, Engineering/Geoscience Professionals must establish, maintain, and follow documented quality management policies and procedures for the following activities:

- Use of relevant professional practice guidelines
- Authentication of professional documents by application of the professional seal
- Direct supervision of delegated professional engineering or professional geoscience activities
- Retention of complete project documentation
- Regular, documented checks using a written quality control process
- Documented field reviews of engineering or geoscience designs and/or recommendations during implementation or construction
- Where applicable, documented independent review of structural designs prior to construction
- Where applicable, documented independent review of high-risk professional activities or work prior to implementation or construction

Engineering/Geoscience Professionals employed by a Registrant firm are required to follow the quality management policies and procedures implemented by the Registrant firm as per the Engineers and Geoscientists BC permit to practice program.

4.1.1 USE OF PROFESSIONAL PRACTICE GUIDELINES

Engineering/Geoscience Professionals are required to comply with the intent of any applicable professional practice guidelines related to the engineering or geoscience work they undertake. As such, Engineering/Geoscience Professionals must implement and follow documented procedures to ensure they stay informed of, knowledgeable about, and meet the intent of professional practice guidelines that are relevant to their professional activities or services. These procedures should include periodic checks of the Engineers and Geoscientists BC website to ensure that the latest versions of available guidance is being used.

For more information, refer to the *Quality Management Guides – Guide to the Standard for the Use of Professional Practice Guidelines* (Engineers and Geoscientists BC 2021a), which also contains guidance for how an Engineering/Geoscience Professional can appropriately depart from the guidance provided in professional practice guidelines.

4.1.2 AUTHENTICATING DOCUMENTS

Engineering/Geoscience Professionals are required to authenticate (seal with signature and date) all documents, including electronic files, that they prepare or deliver in their professional capacity to others who will rely on the information contained in them. This applies to documents that Engineering/Geoscience Professionals have personally prepared and those that others have prepared under their direct supervision. In addition, any Document that is authenticated by an individual Engineering/Geoscience Professional must also have a permit to practice number visibly applied to the document. A permit to practice number is a unique number that a Registrant firm receives when they obtain a permit to practice engineering or geoscience in British Columbia (BC).

Failure to appropriately authenticate and apply the permit to practice number to documents is a breach of the Bylaws.

All Landslide Assessment Reports should be sealed, as should the Landslide Assurance Statement provided in Appendix D.

For more information, refer to the *Quality Management Guides – Guide to the Standard for the Authentication of Documents* (Engineers and Geoscientists BC 2021d).

4.1.3 DIRECT SUPERVISION

Engineering/Geoscience Professionals are required to directly supervise any engineering or geoscience work they delegate. When working under the direct supervision of an Engineering/Geoscience Professional, an individual may assist in performing engineering or geoscience work, but they may not assume responsibility for it. Engineering/Geoscience Professionals who are professional licensees engineering or professional licensees geoscience may only directly supervise work within the scope of their license.

When determining which aspects of the work may be appropriately delegated using the principle of direct supervision, the Engineering/Geoscience Professional having ultimate responsibility for that work should consider:

- the complexity of the project and the nature of the risks associated with the work;
- the training and experience of individuals to whom the work is delegated; and
- the amount of instruction, supervision, and review required.

Careful consideration must be given to delegating field reviews. Due to the complex nature of field reviews, Engineering/Geoscience Professionals with overall responsibility should exercise judgment when relying on delegated field observations, and should conduct a sufficient level of review to have confidence in the quality and accuracy of the field observations. When delegating field review activities, Engineering/Geoscience Professionals must document the field review instructions given to a subordinate. (See Section 4.1.6 Documented Field Reviews During Implementation or Construction.)

For more information, refer to the *Quality Management Guides – Guide to the Standard for Direct Supervision* (Engineers and Geoscientists BC 2021e).

4.1.4 RETENTION OF PROJECT DOCUMENTATION

Engineering/Geoscience Professionals are required to establish and maintain documented quality management processes to retain complete project documentation for a minimum of ten (10) years after the completion of a project or ten (10) years after an engineering or geoscience document is no longer in use.

These obligations apply to Engineering/Geoscience Professionals in all sectors. Project documentation in this context includes documentation related to any ongoing engineering or geoscience work, which may not have a discrete start and end, and may occur in any sector.

Many Engineering/Geoscience Professionals are employed by firms, which ultimately own the project documentation. Engineering/Geoscience Professionals are considered compliant with this quality management requirement when reasonable steps are taken to confirm that (1) a complete set of project documentation is retained by the organizations that employ them, using means and methods consistent with the Engineers and Geoscientists BC Bylaws and quality management standards; and (2) they consistently adhere to the documented policies and procedures of their organizations while employed there.

For more information, refer to the *Quality Management Guides – Guide to the Standard for Retention of Project Documentation* (Engineers and Geoscientists BC 2021f).

4.1.5 DOCUMENTED CHECKS OF ENGINEERING AND GEOSCIENCE WORK

Engineering/Geoscience Professionals are required to perform a documented quality checking process of engineering and geoscience work, appropriate to the risk associated with that work. All Engineering/ Geoscience Professionals must meet this quality management requirement.

The checking process should be comprehensive and address all stages of the execution of the engineering or geoscience work. This process would normally involve an internal check by another Engineering/ Geoscience Professional within the same organization. Where an appropriate internal checker is not available, an external checker (i.e., one outside the organization) must be engaged. In some instances, self-checking may be appropriate. Where internal, external, or self-checking has been carried out, the details of the check must be documented. The documented quality checking process must include checks of all professional deliverables before being finalized and delivered.

Engineering/Geoscience Professionals are responsible for ensuring that the checks being performed are appropriate to the level of risk associated with the item being checked. Considerations for the level of checking should include:

- the type of item being checked;
- the complexity of the subject matter and underlying conditions related to the item;
- the quality and reliability of associated background information, field data, and Elements at Risk; and
- the Engineering/Geoscience Professional's training and experience.

As determined by the Engineering/Geoscience Professional, the individual doing the checking must have current expertise in the discipline of the type of work being checked, be sufficiently experienced and have the required knowledge to identify the elements to be checked, be objective and diligent in recording observations, and understand the checking process and input requirements.

For more information, refer to the *Quality Management Guides – Guide to the Standard for Documented Checks of Engineering and Geoscience Work* (Engineers and Geoscientists BC 2021g).

4.1.6 DOCUMENTED FIELD REVIEWS DURING IMPLEMENTATION OR CONSTRUCTION

Field reviews are reviews conducted at the site of the construction or implementation of the engineering or geoscience work. They are carried out by an Engineering/Geoscience Professional or a subordinate acting under the Engineering/Geoscience Professional's direct supervision (see Section 4.1.3 Direct Supervision).

Field reviews enable the Engineering/Geoscience Professional to ascertain whether the construction or implementation of the work substantially complies in all material respects with the engineering or geoscience concepts or intent reflected in the engineering or geoscience documents prepared for the work.

For more information, refer to the *Quality Management Guides – Guide to the Standard for Documented Field Reviews During Implementation or Construction* (Engineers and Geoscientists BC 2021h).

4.1.7 DOCUMENTED INDEPENDENT REVIEW OF HIGH-RISK PROFESSIONAL ACTIVITIES OR WORK

Engineering/Geoscience Professionals must perform a documented risk assessment prior to initiation of a professional activity or work, to determine if that activity or work is high risk and requires a documented independent review.

If the activities or work are deemed high risk, and an independent review is required, the results of the risk assessment must be used to (1) determine the appropriate frequency of the independent review(s); and (2) determine if it is appropriate for the independent reviewer to be employed by the same firm as the Qualified Professional, or if the independent reviewer should be employed by a different firm.

The documented independent review of high-risk professional activities or work must be carried out by an Engineering/Geoscience Professional with appropriate experience in the type and scale of the activity or work being reviewed, who has not been involved in preparing the design.

The documented independent review must occur prior to implementation or construction; that is, before the professional activity or work is submitted to those who will be relying on it.

The term "risk" refers to the potential Consequences to Clients and the public multiplied by the likelihood of such Consequences occurring, which mostly pertains to human life loss or economic losses but may also refer to environmental losses. Landslide Assessments often involve potentially lethal Consequences, as Landslides have typically enough impact force to injure or kill people inside and outside buildings. A high-risk activity is therefore defined as "one in which the studied process or processes have the potential of leading to life loss or substantial economic or environmental loss in the return period range considered for the respective study." With respect to the tables in Appendix C: Landslide Assessment – Level of Effort, class 0 assessments are not typically classified as high-risk activities. However, if a high-risk activity is not characterized correctly in a class 0 study, future development approvals could proceed. Classes 1 to 3 are classified as high-risk activities that require independent review.

For more information, refer to the *Quality Management Guides – Guide to the Standard for Documented Independent Review of High-Risk Activities or Work* (Engineers and Geoscientists BC 2021c).

4.2 OTHER QUALITY MANAGEMENT REQUIREMENTS

Engineering/Geoscience Professionals must also be aware of any additional quality management requirements from other sources that are relevant to their work, which may include but are not limited to:

- legislation and regulations at the local, regional, provincial, and federal levels;
- policies of authorities having jurisdiction at the local, regional, provincial, and federal levels;
- Agreements and service contracts between clients and Engineering/Geoscience Professionals or their firms; and/or
- standards for engineering or geoscience firms, particularly those that apply to quality management system certification, such as the ISO 9000 family.

Engineering/Geoscience Professionals should assess any areas of overlap between the Engineers and Geoscientists BC quality management requirements and the requirements of other applicable sources. If the requirements of different sources overlap, Engineering/Geoscience Professionals should attempt to meet the complete intent of all requirements.

Where there are conflicts between requirements, Engineering/Geoscience Professionals should negotiate changes or waivers to any contractual or organizational requirements which may conflict with requirements of legislation, regulation, or the Engineers and Geoscientists BC Code of Ethics. Generally, no contractual obligation or organizational policy that may apply to an Engineering/Geoscience Professional will provide justification or excuse for breach of any of the Engineering/Geoscience Professional's obligations under any legislation, regulation, or the Code of Ethics. Where such conflicts arise and cannot be resolved, Engineering/Geoscience Professionals should consider seeking legal advice from their own legal advisers on their legal rights and obligations in the circumstances of the conflict, and they may also seek practice advice from Engineering and Geoscientists BC on any related ethical dilemma that they may face in the circumstances.

4.3 PRACTICE ADVICE

Engineers and Geoscientists BC provides their Registrants and others with assistance addressing inquiries related to professional practice and ethics.

Practice advisors at Engineers and Geoscientists BC can answer questions regarding the intent or application of the professional practice or quality management aspects of these guidelines.

To contact a practice advisor, email Engineers and Geoscientists BC at practiceadvisor@egbc.ca.

5.0 PROFESSIONAL REGISTRATION & EDUCATION, TRAINING, AND EXPERIENCE

5.1 PROFESSIONAL REGISTRATION

Qualified Professionals have met minimum education, experience, and character requirements for admission to their professions. However, the educational and experience requirements for professional registration do not necessarily constitute an appropriate combination of education and experience for Landslide Assessments. Professional registration alone does not automatically qualify a Qualified Professional to take professional responsibility for all types and levels of professional services in this area of practice.

It is the responsibility of Qualified Professionals to determine whether they are qualified by training and/or experience to undertake and accept responsibility for carrying out Landslide Assessment (Code of Ethics Principle 2).

As summarized in Appendix A: Legislative Framework of these guidelines, the following are the statutes that require professional registration in relation to Landslide Assessments for proposed Residential Development in British Columbia (BC):

- The *Land Title Act*, Section 86(1)(d)(i) indicates that Landslide Assessments for subdivision approval, when required, must be carried out by a professional engineer or professional geoscientist "experienced in geotechnical engineering."
- The *Local Government Act*, Section 920(11) indicates that, for a development permit, the Local Government may require a report from a professional engineer "with experience relevant to the applicable matter."
- The *Community Charter*, Section 56(1) indicates that Landslide Assessments for Construction, when required, must be carried out by a professional engineer or professional geoscientist "with experience or training in geotechnical study and geohazard assessments."
- The *Local Government Act*, Section 910(5) indicates that, for flood plain bylaw exemption, a professional engineer or professional geoscientist "experienced in geotechnical engineering" is required.
- The provincial document "Flood Hazard Area Land Use Management – Guidance for Selection of Qualified Professionals and Preparation of Flood Hazard Assessment Reports" associated with the *Local Government Act*, Section 910 (BC MWLAP 2004) indicates that a Qualified Professional is a professional engineer or professional geoscientist with "geotechnical engineering experience and expertise in river engineering and hydrology, and in appropriate cases…debris flow…processes."
- The *Riparian Areas Protection Regulation*, Section 21(2)(iv, vi) indicates that professional engineers or geoscientists are qualified to conduct assessments "within the scope of professional practice for the individual's profession, and under the code of ethics of Engineers and Geoscientists BC, and is subject to disciplinary action by that regulatory body."

A professional engineer as described above is typically registered with Engineers and Geoscientists BC in the discipline of geological engineering, mining engineering, or civil engineering.

A professional geoscientist as described above is typically registered with Engineers and Geoscientists BC in the discipline of geology or environmental geoscience. Although the *Land Title Act* and the *Local Government Act* refer to a professional geoscientist "experienced in geotechnical engineering," by definition a professional geoscientist is not experienced in engineering. Engineers and Geoscientists BC interprets the *Land Title Act* and the *Local Government Act* to mean a "professional geoscientist experienced in geotechnical study," similar to that expressed in the *Community Charter*.

On this basis, the Qualified Professional who provides designs such as reinforced or mechanically stabilized slopes, retaining walls, and other geotechnical structures to reduce Landslide Hazards and/or Landslide Risks requires registration with Engineers and Geoscientists BC as an Engineering Professional. The Qualified Professional who investigates or interprets complex geological conditions, geomorphic processes, and geochronology in support of Landslide Assessments is typically registered with Engineers and Geoscientists BC as a Geoscience Professional in the discipline of geology or environmental geoscience, or as an Engineering Professional in the discipline of geological engineering.

5.2 EDUCATION, TRAINING, AND EXPERIENCE

Qualified Professionals who take responsibility for Landslide Assessments must adhere to the second principle of the Engineers and Geoscientists BC Code of Ethics, which is to "practice only in those fields where training and ability make the registrant professionally competent" and, therefore, must evaluate their own qualifications and must possess the appropriate education, training, and experience to provide the services. Registration with Engineers and Geoscientists BC alone does not satisfy this inquiry.

The level of education, training, and experience required of Qualified Professionals should be adequate for the complexity of the project. This section describes indicators that Qualified Professionals can use to determine whether they have an appropriate combination of education and experience.

Note that these indicators are not an exhaustive list of education and experience types that are relevant to Landslide Assessment. Satisfying one or more of these indicators does not automatically imply competence to perform Landslide Assessments.

5.2.1 EDUCATIONAL INDICATORS

Certain indicators show that Qualified Professionals have received education that might qualify them to participate professionally in Landslide Assessment work. Educational indicators are subdivided into formal education (such as university or engineering school) and informal education (such as continuing education).

Formal educational indicators include having obtained an undergraduate-level degree in geotechnical engineering or geology, or a related engineering or geoscience field from an accredited engineering or geoscience program, with specific focus in the following areas:

- Bedrock geology
- Structural geology
- Surficial geology, engineering performance of soils
- Soil and rock mechanics
- Geomorphology
- Hydrology and groundwater geology
- Air photo interpretation

Informal educational indicators include having participated in or undertaken one or more of the following:

- Training courses facilitated by the Qualified Professional's employer that focus on the above topics

- Continuing education courses or sessions offered by professional organizations (such as Engineers and Geoscientists BC) that focus on the above topics
- Conferences or industry events that focus on the above topics
- A rigorous and documented self-study program involving a structured approach that contains materials from textbooks and technical papers on the above topics

Completion of the above courses does not make a professional engineer or geoscientist a Landslide Assessment specialist but helps demonstrate the basis of a deeper understanding that is attained through the additional professional experiences listed below. This type of education should be considered when determining whether an Engineering/Geoscience Professional has sufficient knowledge to undertake Landslide Assessments.

5.2.2 EXPERIENCE INDICATORS

Certain indicators show that Qualified Professionals have an appropriate combination of experience that might qualify them to participate professionally in Landslide Assessments.

Experience indicators include having completed one or more of the following:

- For an extended duration (greater than one year) and/or as an Engineering-in-Training (EIT)/ Geoscientist-in-Training (GIT), participated in Landslide Assessment under the direct supervision of an Qualified Professional with an appropriate combination of education and experience
- Participated in past projects working alongside other Qualified Professionals, and developed a sufficient knowledge of the techniques, methods, and standard of practice for Landslide Assessment
- Participated in academic or industry working groups that focus on practical lessons learned from experiences performing Landslide Assessment in BC or other jurisdictions.

As the complexity of the terrain increases, and depending on the location in the province, the minimum qualifications should be supplemented by training and experience in additional specialty subject areas as required such as the following:

- Quaternary geology
- Detailed kinematic analysis of bedrock structure and failure modes
- Petrology
- Sedimentology
- Permafrost
- Landslide mitigation and remediation

Specialists may have to be retained to provide experience in some of the above subject areas.

6.0 REFERENCES AND RELATED DOCUMENTS

Legislation referenced in the main guidelines and the appendices appears in Section 6.1 Legislation.

Documents cited in the main guidelines appear in Section 6.2 References and Section 6.3 Codes and Standards; those cited in the appendices appear in the reference list at the end of each corresponding appendix.

Additional related documents that may be of interest to users of these guidelines appear in Section 6.4 Related Documents; some appendices also contain a similarly titled section at the end of the appendix.

6.1 LEGISLATION

The following legislation is referenced in these guidelines:

Community Charter [SBC 2003], Chapter 26.

Forest and Range Practices Act [SBC 2002], Chapter 69.

Forest Act [RSBC 1996], Chapter 157.

Land Act [RSBC 1996], Chapter 245.

Land Title Act [RSBC 1996], Chapter 250.

Local Government Act [RSBC 1996], Chapter 323.

Professional Governance Act [SBC 2018], Chapter 47.

Riparian Areas Protection Act [SBC 1997], Chapter 21.

Riparian Areas Protection Act, Riparian Areas Protection Regulation, BC Reg 178/2019.

Water Sustainability Act [SBC 2014], Chapter 15.

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6.2 REFERENCES

The following documents are referenced in these guidelines:

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6.3 CODES AND STANDARDS

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7.0 APPENDICES

APPENDIX A: LEGISLATIVE FRAMEWORK

This appendix summarizes the legislative framework governing Landslide Assessments at the time of publication; Qualified Professionals (QPs) should refer to the actual legislation for details.

A.1 INTRODUCTION

Proposed Residential Development in British Columbia is governed by several provincial statutes. The statutes that require Landslide Assessments by QPs include the:

- *Land Title Act* (RSBC 1996, Chapter 250);
- *Local Government Act* (RSBC 2015, Chapter 1);
- *Community Charter* (SBC 2003, Chapter 26); and
- *BC Building Code 2018*.

In addition, the *Riparian Areas Protection Act* directs Local Governments to protect riparian areas during residential, commercial, and industrial development by ensuring that a qualified environmental professional (QEP) conducts a science-based assessment of proposed activities that may cause harm to fish habitat. Where such developments may cause Landslides, Landslide Assessments are required.

A.2 LAND TITLE ACT – SUBDIVISION APPROVALS

The *Land Title Act*, Division 4, Section 86, contains provisions for refusing to approve a subdivision if the Approving Officer considers that the land is subject, or could reasonably be expected to be subject, to flooding, [soil] erosion, land slip, or [snow] avalanche.

These guidelines address only Landslides—referred to as "land slip" in the *Land Title Act*. They do not address the other natural hazards listed there, except as related to Landslides.

The *Land Title Act*, Section 86, also indicates that if the land to be subdivided is subject, or could reasonably be expected to be subject, to Landslides, as a condition of subdivision approval the Approving Officer may require either or both of the following:

- a report certified by a professional engineer or professional geoscientist experienced in Geotechnical Engineering that the land may be used safely for the use intended; and/or
- one or more registered Covenants restricting the use of the land.

A.3 LOCAL GOVERNMENT ACT – DEVELOPMENT PERMITS

The *Local Government Act*, Division 7, Sections 488 and 491, states that a Local Government's Official Community Plan may establish a development permit area for a number of reasons, one of which is to protect development from hazardous conditions. Hazardous conditions, as defined in the *Local Government Act*, include flooding, mud flows, torrents of debris, [soil] erosion, land slip, rockfalls, subsidence, tsunami, [snow] avalanche, or wildfire.

These guidelines address only Landslides—referred to as "mud flows", "debris torrents"[9], "land slip", and "rockfalls" in the *Local Government Act*. They do not address the other natural hazards listed there, except as related to Landslides.

[9] For the purpose of these guidelines, debris flows, debris torrents, and mud flows are collectively considered as debris flows.

A development permit may be required by a Local Government before Residential Development can occur within a development permit area. Per the *Local Government* Act, Section 491, before issuing a development permit, the Local Government may require a report certified by a professional engineer with experience relevant to the applicable matter, to assist the Local Government in determining what conditions or requirements it will impose.

Typically, a planner and/or the council or board of a Local Government reviews the professional engineer's report, and then determines what conditions or requirements to include in the development permit.

Note that development permits and building permits are different. Development permits precede building permits, and both may be required in jurisdictions that have an Official Community Plan and where Residential Development may be exposed to Landslides.

A.4 COMMUNITY CHARTER – BUILDING PERMITS

The *Community Charter*, Division 8, Section 56, contains provisions for not issuing a building permit if a Building Inspector considers that Construction would be on land that is subject to or is likely to be subject to flooding, mud flows, debris flows, debris torrents, [soil] erosion, land slip, rockfalls, subsidence, or [snow] avalanche.

These guidelines address only Landslides—referred to as "mud flows", "debris flows", "debris torrents", "land slips", and "rockfalls" in the *Community* Charter. They do not address the other natural hazards listed there, except as related to Landslides.

The *Community Charter*, Section 56, indicates that if Construction is on land that is subject, or is likely to be subject, to Landslides, as a condition of a building permit the Building Inspector may require a certified report by a qualified professional (defined therein as a professional engineer or a professional geoscientist with experience or training in geotechnical study and geohazard assessments) that the land may be used safely for the use intended.

The Building Inspector may issue a building permit if:

- a qualified professional (as defined in the *Community Charter*) reports the land may be used safely for the intended use if the land is used in accordance with conditions specified in the qualified professional's report; and
- there is a registered Covenant restricting the use of the land.

If the qualified professional determines the land may not be used safely for the intended use, the Building Inspector must not issue a building permit.

A.5 LOCAL GOVERNMENT ACT – FLOOD PLAIN BYLAW VARIANCES OR EXEMPTIONS

The *Local Government Act*, Division 13, Section 524, addresses Construction requirements in relation to flood plains, and states that a Local Government, in making bylaws under this section, must (a) consider the provincial guidelines, and (b) comply with the provincial regulations and a plan or program the Local Government has developed under those regulations. To date, there are no such provincial regulations, and therefore no Local Government plans or programs have been developed under this type of regulation.

Section 524 does not refer specifically to Landslides; however, the *Flood Hazard Area Land Use Management Guidelines* (BC MWLAP 2004a), which guides a Local Government in making bylaws under Section 524, addresses "debris flows", a type of Landslide as defined in these guidelines.

The flood hazard guidelines state that, although development should be discouraged in areas prone to debris flows, consent to develop [variance] may be granted, with standard requirements as established for alluvial fan in section 3.3 [of those guidelines], where:

- there is no other land available, and

- where an assessment of the land by a suitably Qualified Professional indicates that development may occur safely (BC MWLAP 2004a).

Section 524 also indicates that a Local Government may grant a bylaw exemption if it considers the exemption to be advisable and it is consistent with the provincial guidelines, or the Local Government has received a report that the land may be used safely for the use intended, as certified by either:

- a professional engineer or professional geoscientist experienced in Geotechnical Engineering; or
- a person in a class prescribed by the minister in the *Local Government Act*, Section 524 (however, to date no class of persons has been prescribed).

Typically, a planner and/or the council or board of a Local Government reviews the professional engineer's or professional geoscientist's report, and then determines what conditions or requirements to include in the bylaw or to exempt from the bylaw.

In addition, the *Flood Hazard Area Land Use Management, Guidance for Selection of Qualified Professionals and Preparation of Flood Hazard Assessment Reports* (BC MWLAP 2004b) indicates that a qualified professional in this context is:

- a professional engineer or professional geoscientist with Geotechnical Engineering experience and expertise in river engineering and hydrology, and in appropriate cases, …debris flow…processes.

A.6 BC BUILDING CODE AMENDMENTS RELATED TO SEISMIC SLOPE STABILITY AND TECHNICAL GUIDANCE

The following excerpts from the *BC Building Code 2018* contains wording pertinent to seismic slope stability analysis.

- Part 4, Division B, Part 4, Article 4.1.8.17. Site Stability

  "1) The potential for slope instability and its consequences, such as slope displacement, shall be evaluated based on site-specific material properties and ground motion parameters in Subsection 1.1.3., as modified by Article 4.1.8.4., and shall be taken into account in the design of the structure and its foundations."

- Part 9, Division B, Part 9, Article 9.4.4.4. Soil Movement

  "2) The potential for slope instability and its consequences, such as slope displacement, shall be evaluated based on site-specific material properties and ground motion parameters in Subsection 1.1.3 and shall be taken into account in the design of the structures and its foundations."

The Information Bulletin B10-01, "British Columbia Building Code Amendments Related to Seismic Slope Stability and Technical Guidance" (BC Building and Safety Policy Branch 2010), summarizes two changes:

- the consideration of potential for slope instability and its Consequences at a building site is now an explicit requirement in designs of structures and their foundations; and
- the seismic hazard probability level to be used in seismic slope analysis is Ground Motions with a probability of exceedance of 2% in 50 years (annual probability of 1:2,475), as referenced in Subsection 1.1.3 of Division B.

As a result of the second bullet, the seismic hazard probability levels for structural design and for seismic slope analysis are now the same: Ground Motions with a probability of exceedance of 2% in 50 years (annual probability of 1:2,475).

A.7 RIPARIAN AREAS PROTECTION REGULATION

The *Riparian Areas Protection Regulation*, Section 15, when describing the terms of the assessment report, stipulates that in the case of a detailed assessment, any potential hazards posed by the proposed development to natural features, functions, or conditions in the streamside protection and enhancement area must be identified.

Further, in Section 16, for each potential hazard identified under section 15 (2) I, if applicable, an assessment report must:

(a) explain how the design of the proposed development will avoid the hazard; or

(b) recommend measures to be taken to avoid the hazard.

Individuals who may act as qualified environmental professionals (QEPs) under the *Riparian Areas Protection Regulation* include professional engineers or professional geoscientists who are conducting the portion of the assessment that is within their area of expertise, as identified in the regulation. The QEP must be acting under their professional association's code of ethics and be subject to the organization's disciplinary action.

A.8 REFERENCES – APPENDIX A

The following documents are referenced in Appendix A of these guidelines:

BC Building and Safety Policy Branch. 2010. Information Bulletin B10-01, British Columbia Building Code Amendments Related to Seismic Slope Stability and Technical Guidance. January 18, 2010. Victoria, BC: Province of BC. [accessed: 2021 Dec 10]. https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/construction-industry/building-codes-and-standards/bulletins/b10_01_seismic_slope_stability.pdf.

BC Ministry of Water, Land and Air Protection (MWLAP). 2004a. Flood Hazard Area Land Use Management Guidelines. May 2004. [Amended by Ministry of Forests, Lands, Natural Resource Operations and Rural Development, January 2018 and August 2011]. Victoria, BC: Province of BC. [accessed: 2021 Dec 10]. https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/integrated-flood-hazard-mgmt/flood_hazard_area_land_use_guidelines_2017.pdf.

BC MWLAP. 2004b. Flood Hazard Area Land Use Management. Guidance for Selection of Qualified Professionals and Preparation of Flood Hazard Assessment Reports. [accessed: 2021 Dec 10]. https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/integrated-flood-hazard-mgmt/selection_of_qualified_professionals_guidance.pdf.

APPENDIX B: LANDSLIDE ASSESSMENT – DETERMINING THE LEVEL OF EFFORT

The information in this appendix supports Section 3.3.1.2 Level of Effort.

To go directly to the level of effort tables, see subsection B.2.4 Level of Effort Tables B-1 to B-6.

B.1 INTRODUCTION

The appropriate level of effort to be applied to a Landslide Assessment varies with the size of the study area, the character of the Landslide (fast or slow moving), and the Consequences to the Elements at Risk. The sample time frame, or time depth into the past, that needs to be explored via desktop and field investigations to develop a frequency-magnitude model also affects the level of effort.

The overarching idea is that the level of effort expended in completing a hazard assessment increases with the number of people, or value of assets, already or potentially affected. This is aligned with the basic principles of risk assessments. Therefore, in this context, the level of effort will be determined by the interaction between the exposure inherent in the existing or proposed development and the adopted or defined safety criteria. The level of effort will also reflect the practical constraints of geoscientific feasibility and the available budget.

In British Columbia (BC), most Landslide Assessments are conducted for legislated developments, which are typically of small scale (i.e., one or two homes). In these cases, and disregarding affordability, very detailed studies are not warranted, given the comparatively low life-loss potential or economic damage associated with the development or redevelopment. Furthermore, detailed investigations may be limited by access constraints.

The return period (i.e., annual probability) classes associated with each level of effort shown in this appendix are minimum values for the specified development size, and they are set with past BC practice and international practice in mind. When rare hazards have been previously identified through a literature review that includes past consultant reports, or geological evidence for them is apparent (e.g., gravitational spreading, or sackung) or has been discovered (e.g., in test pits), then the Qualified Professional (QP) should not exclude higher return period classes than the minimum values reported herein.

At any project scale, it is important to convey the degree of, and uncertainty associated with, residual risk (see Appendix G: Strategies for Uncertainty Reduction). The minimum return periods do not imply that only one hazard scenario (e.g., the 1:500-year event) be considered. Rather, project-specific probability or magnitude classes should be used, where possible, to support the assessment (e.g., 1:10 to 1:30-year event; 1:30 to 1:100-year event), and subscenarios (e.g., avulsions in the case of debris flows or channelized rock avalanches) can be added. The choice of the return period class boundaries lies with the QP unless otherwise specified by the Client or Approving Authority.

Although frequency data are often not available in BC, guidance on the return periods to be used for Landslide Hazard assessments ranges from 500 years to 2,500 years (Engineers and Geoscientists BC 2018) for debris flows and up to 10,000 years (BC MOTI 2015) for life-threatening Landslides or catastrophic events affecting new communities (Cave 1993; see also Table C - 1 in Appendix C: Review of Levels of Landslide Safety).

In countries with lower return-period standards for Landslide Hazard or Landslide Risk assessments, there are many potential reasons for this apparent higher tolerance of residual risk, namely the implication that higher frequency lethal hazards drive the risk, or that cost-benefit analysis concludes further risk reduction is unaffordable, or some other factors dictated by population density, physiographic context, or historical precedent.

B.2 LEVEL OF EFFORT TABLES

B.2.1 OVERVIEW

A Landslide Assessment may be hazard-based or risk-based (see Section 3.2 Study Types, Figure 1). The type of analysis is decided by the Approving Authority, the Client, or the QP, depending on whether the assessment is for an existing development or a proposed development, and whether local or provincial documents provide guidance on the type of assessment.

The guidance provided in subsection B.2.4 Level of Effort Tables B-1 to B-6 is not intended to prevent a QP or an Approving Authority from selecting other procedures they deem appropriate, when the use and application of those procedures can be supported by a suitable level of analysis and relevant documentation. Rather, the level of effort tables are intended to guide decisions about the appropriate level of effort to be applied depending on the objective of the assessment. This includes the issues that need to be addressed, the level of detail required, and the types of analyses to be conducted so specialists can be engaged if required.

Each level of effort table organizes hazard assessments into four classes: class 0 to 3. Each class comprises a level of effort, typical deliverables, applications, and time horizons to be explored that are associated with minimum Landslide return periods or annual probabilities.

The guiding principle is that increases in loss potential necessitate increased effort and larger return periods, to account for extreme events that could lead to catastrophic loss. This is reflected in the long-used Cave (1993) matrices for Residential Development in the Fraser Valley Regional District (FVRD 2020).

Similar approaches apply to dam assessments (CDA 2013), where greater loss potential prompt accounting for higher design return periods (realizing that there is a difference in design versus the basis for hazard mapping or quantitative risk assessments), to avalanche assessments (Canadian Avalanche Association 2016), and to flood assessments (Engineers and Geoscientists BC 2018).

B.2.2 HOW THE TABLES WORK

The tables in subsection B.2.4 Level of Effort Tables B-1 to B-6 address the Landslide types set out in the list below. Different Landslide types require variable approaches and methods. Landslide types are combined where assessment methods would be similar.

- Slowly creeping Landslides, such as rock creeps in soft rocks and earth flows (Table B - 1)
- Debris flows, debris slides, and debris avalanches, including flow slides (Table B - 2)
- Rockfall and rockslides (Table B - 3)
- Rock avalanches (Table B - 4)
- Slumps and spreads (Table B - 5)
- Slope stability analysis (Table B - 6)

Note that for all Landslide Assessments, the bullet points listed in Section 3.3.6 Landslide Assessment Report of the main guidelines apply. The difference between the points listed in tables B-1 to B-6 (under column 3) and those in Section 3.3.6 is that the latter lists all components of a typical Landslide Assessment, while the former lists specific methods regarded as minimum effort.

Note that in tables B-1 to B-6, the key deliverables are examples only and the scope as determined with the Approving Authority or Client may be beyond that noted in those tables.

The first column in each level of effort table organizes hazard assessments into four classes (class 0 to 3); each subsequent column addresses a specific aspect of the assessment:

- **Column 1** specifies the class of assessment (listed from class 0 to 3).
- **Column 2** specifies the application; that is, the scale of development associated with the minimum level of effort.
- **Column 3** describes the typical assessment methods and the environmental and climate change considerations, constituting the minimum level of effort.
  - Note that in some cases, it may not be possible to use certain methods listed in column 3. An example would be because there are no trees available on which to conduct a dendrochronological analysis. In this case, the QP would need to identify reasonable replacement methods.
- **Column 4** lists typical key deliverables of the assessment class, which the QP may determine in consultation with the Client and/or Approving Authority, or which may be requested by the Client and/or Approving Authority themselves.
- **Column 5** defines the minimum return period and the typical time window that the QP should consider in the assessment. The time window is the period during which a particular Landslide activity can be defined. This approach is similar to calculating flood-frequency estimates, where approximately double the record length is generally used to extrapolate higher return periods as illustrated in the following examples:
  - Single home located at the bottom of a potentially debris-avalanche-prone slope:
    - Applying dendrochronology (tree-ring dating) and air photograph analysis may allow the QP to reconstruct a relatively complete record of debris avalanches for up to 300 years. This would be appropriate to use for constructing a frequency-magnitude analysis for a 500-year return period event through extrapolation. Further extrapolation to higher return periods would be possible but would be associated with increasing error and/or uncertainty.
  - Subdivision of more than 50 buildings located at the bottom of the same potentially debris-avalanche-prone slope:
    - The runout and intensity of a debris avalanche would need to be estimated for at least a 5,000-year return period. In practice, this would necessitate excavating test pits, and searching for Landslide colluvium and radiocarbon-datable organics. This would require that at least a 2,000-year record be established where possible.
    - In reality, there may not be an opportunity for test pitting (e.g., lack of permission from Landowners or the area has already been developed). In this case, the QP may need to resort to using a regional cumulative magnitude approach (see Figure 3: Example of a cumulative frequency-magnitude curve for rockfalls and rockslides along four major transportation corridors in southwestern British Columbia).

Regarding return periods, in column 5 of the level of effort tables, the return-period values are derived from earlier guidance by Cave (1992, 1993) and comparisons with similar approaches used in Norway or Switzerland that use those values in hazard and/or risk assessments and land use zoning. However, the values provided here are not exactly mapped to other jurisdictions. For example, the values proposed in these guidelines are more conservative than those used in Switzerland because the historic record length is shorter and thus more prone to uncertainty.

To identify specific hazard scenarios, it is useful to create return period classes (or annual probabilities) in relatively regular intervals (e.g., 0 to 20 years, 20 to 100 years, 100 to 500 years, 500 to 2,500 years, 2,500 to 10,000 years), or by using appropriate mean return period values as proxies for return period classes (e.g., 10 years, 50 years, 200 years, 1,000 years). Classification by return periods may be particularly useful for Landslide processes with a continuum of volumes.

Alternatively, the QP may wish to identify Landslide volume classes, where appropriate, and then assign a return period to those volume classes. The latter is especially important where distinct volume classes are likely to result in different mobilities or changes in the Landslide process.

- For example, a volume class of 0.5 to 3 m^3 may be appropriate for fragmental rockfall, and the associated return period may be 5 years for rockfall of that class to occur. The QP may then identify a volume class of 100 to 2,000 m^3 for rockslides and assign a tentative return period range of 200 to 500 years based on detailed field investigations including dendrogeomorphology and air photo interpretation.
- The same slope may also be affected by rock avalanches with volumes of 5 to 10 million m^3. Those may not have a return period per se, as once the instable rock mass has failed it may not reoccur. In this case, the event may be assigned a future probability of X% in 50 years, which is reflected in Table B - 4.

B.2.3 EXAMPLES OF USING THE TABLES

Each table in subsection B.2.4 Level of Effort Tables B-1 to B-6 organizes hazard assessments into four classes—class 0 to 3—which correspond to the scale of assessment from least to most complex. Each class comprises a level of effort, typical deliverables, applications, and time horizons to be explored that are associated with minimum Landslide return periods or annual probabilities.

Following are examples of scenarios where the QP (and/or the Approving Authority or Client) can use the level of effort table corresponding to a particular Landslide type to determine the minimum deliverables.

- Scenario 1: A request to provide an opinion on whether a proposed or existing development is subject to Landslide Hazards. This is at the low end of the scale of development, so would constitute a class 0 assessment.
  - Providing such an opinion typically does not require detailed investigations.
  - The level of effort would be limited to the following tasks:
    - Desktop analyses of available mapping resources (e.g., bedrock and surficial geology, topographic maps, online satellite imagery, or other imagery)
    - A limited site visit to the field to verify the conclusions obtained from the desktop analysis
  - The outcome would be a letter stating if a Landslide Hazard assessment will be required. If significant hazard potential were identified, the letter should indicate the nature of further assessment required.
- Scenario 2: A Landslide Hazard assessment for a building permit for a single-family home or proposed small subdivision (less than 5 new buildings). This is at the middle of the development scale, so would constitute a class 1 assessment.
  - More detailed investigations would be required, so the level of effort would be increased as appropriate, and the costs of the study would increase proportionally.
  - The level of effort would involve some or all of the following tasks:
    - Background review of anecdotal information obtained from long-term residents, media reports, and grey literature
    - Review of air photo series extending from present day back to earliest flight lines in the late 1920s to 1940s
    - Review of more recent satellite imagery and LiDAR surveys
    - Subsurface exploration to develop a slope stability model or describe stratigraphy

- Various means of age dating of soil layers or land surfaces for frequency analysis
- Mapping of hazard zones based on field evidence, expert judgment, or modelling

– The outcome would be an estimate of the Factor of Safety or hazard level affecting proposed structures; comparison against adopted local or some other applicable risk standards; and establishment of conditions imposed on safe development (i.e., siting constraints, protective measures, Covenant).

- Scenario 3: A Landslide Risk assessment for a new subdivision of 50 buildings at the bottom of a steep rock slope that extends into the alpine. This is at the high end of the development spectrum scale, so would constitute a class 2 or 3 assessment.
  - More elaborate investigative methods would be required, and the time frame for the assessment may be considerably lengthened due to the nature of the data requirements.
  - The level of effort should include several or all of the following methodologies and tasks:
    - Detailed structural geological investigations to identify potential rock mass failure modes, potential rock mass size, failure scenarios, or existence of permafrost
    - Deformation measurements using inclinometers, or stationary GPS
    - Remote sensing change detection using repeat datasets (e.g., LiDAR, photogrammetry, InSAR)
    - Other appropriate techniques at the disposal of the QP relevant to the type of development and complexity of assessment
  - The outcome would be a detailed Risk Assessment, likely with recommendation(s) if the development can proceed, and what type of mitigation measures might be necessary.

B.2.4 LEVEL OF EFFORT TABLES B-1 TO B-6

These level of effort tables follow in this subsection:

- Table B - 1: Types of Risk Assessments for Slowly Creeping Landslides, Such as Rock Creeps in Soft Rocks and Earth Flows
- Table B - 2: Types of Risk Assessments for Debris Flows, Debris Slides, and Debris Avalanches, including Flow Slides
- Table B - 3: Types of Risk Assessments for Rockfall and Rockslides
- Table B - 4: Types of Risk Assessments for Rock Avalanches
- Table B - 5: Types of Risk Assessments for Slumps and Spreads
- Table B - 6: Types of Static and Seismic Slope Stability Analysis

Table B - 1: Types of Risk Assessments for Slowly Creeping Landslides, Such as Rock Creeps in Soft Rocks and Earth Flows

Note: For rock types that could detach catastrophically, Table B - 4: Types of Risk Assessments for Rock Avalanches applies.

CLASS	APPLICATIONS	TYPICAL ASSESSMENT METHODS WITH CLIMATE CHANGE AND ENVIRONMENTAL CONSIDERATIONS	KEY DELIVERABLES	MINIMUM RETURN PERIOD & TYPICAL TIME WINDOW
0	• Low potential for loss of life due to slow deformation from Landslides, but could occur indirectly from ruptures and explosions of gas pipelines, or secondary hazards caused by ruptured watermains • Types of projects: – Renovations, expansions, new single houses, new duplexes • Applies only to proposed developments located downslope of the Landslide, unless it can be ascertained that the Landslide is relict	• Conduct a background review of grey and peer-reviewed literature; review legislated requirements • Conduct site visit and qualitative assessment of Landslide Hazard • Examine LiDAR information, if available • Identify any very-low-hazard surfaces in the consultation area (e.g., nearby competent bedrock ridges) • Review air photos to determine changes in morphology and possible movement rates • Describe potential climate change effects (not typically quantified) • Identify and qualify upstream mass movement processes or undercutting that could trigger creep accelerations • Identify the possibility of partial rapid mass movements within the creeping Landslide mass • Assess the effects of Landslide surface alterations	• A document describing the geomorphic setting and hazard zones • Descriptions of, designations for, and mapping of "safe" building sites • Description of siting constraints	• Return periods are not applicable to slowly creeping Landslide types. • The Qualified Professional (QP) should realize that slow-moving Landslides can accelerate, especially given changed conditions (e.g., undercutting, permafrost degradation, precipitation increases, artificial or Landslide loading). • The question then focuses on the probability of such accelerations, rather than a return period or Landslide movement • See Section 3.2 Study Types for tolerance of Landslide movement rates. • Key questions revolve around the exceedance probability of critical movement rates leading to a specific damage scenario • The QP should attempt to reconstitute movement rates, if at all possible, for as long back as possible, given the investigative methods available
1	• Possible loss of life even for single homes or urban developments • Types of projects: – Small subdivision: ▪ <5 single-family lots	• All that was completed for Class 0 • Employ change detection methods (LiDAR or photogrammetry) to characterize average movement rates • Assess climate change effects in terms of possible changes in the frequency and/or magnitude of the Landslide in question • Employ borehole instrumentation with inclinometers and piezometers to understand depth of shear zone(s), phreatic surface oscillations, and pore water pressures	• A report including cross-sections and longitudinal sections with observed surface water, creep velocity, and qualitative description of recorded historic events • If significant watershed changes are detected, a determination of how this may affect watershed hydrology and connection to movement rates • Hazard map based on movement rates	
2	• Types of projects: – Medium to large subdivision: ▪ 6 to 50 single-family lots ▪ New subdivisions	• All that was completed for Class 1 • Conduct detailed analysis of structural geology and failure kinematics • Employ instrumentation to monitor deformation and groundwater for at least one year • Quantify the likelihood and magnitude of a partial rapid mass movement • Conduct a simple time series analysis of climate data to examine if movement rates are related to climate • Review climate change predictions for the study region, and include the results in the assessment, if appropriate • Quantitative risk assessment (QRA) recommended • Conduct statistical analysis of climate data to predict movement rates • Quantify climate change effects as much as possible given current understanding, specifically noting whether climate change effects could lead to a sudden acceleration of movement	• All that was provided for Class 1 • Sections on engineering geology and climate data analysis • Presentation of QRA results	

CLASS	APPLICATIONS	TYPICAL ASSESSMENT METHODS WITH CLIMATE CHANGE AND ENVIRONMENTAL CONSIDERATIONS	KEY DELIVERABLES	MINIMUM RETURN PERIOD & TYPICAL TIME WINDOW
3	• Types of projects: – Large to very large subdivisions (new towns and townships) ▪ >50 single-family lots ▪ New subdivisions	• All that was completed for Class 2 • Perform drilling through the Landslide to understand material characteristics and extrapolate movement rates • Conduct radiometric dating of organics in closed depressions • Perform a deterministic and probabilistic runout analysis, in case sudden movement accelerations are expected • QRA required	• All that was provided for Class 2 • Summary of drilling results • Summary of material properties • Opinions on feasibility of Landslide stabilization	

NOTES:

Abbreviations: QP = Qualified Professional; QRA = quantitative risk assessment

Table B - 2: Types of Risk Assessments for Debris Flows, Debris Slides, and Debris Avalanches, including Flow Slides

Note: The Qualified Professional (QP) can choose lower annual probabilities (higher return periods), where applicable.

CLASS	APPLICATIONS	TYPICAL ASSESSMENT METHODS WITH CLIMATE CHANGE AND ENVIRONMENTAL CONSIDERATIONS	KEY DELIVERABLES	MINIMUM RETURN PERIOD & TYPICAL TIME WINDOW
0	• Types of projects: – Renovations, expansions, new single houses, new duplexes	• Conduct a background review of grey and peer-reviewed literature; review legislated requirements • Provide air photo interpretation, where appropriate • Examine LiDAR information, if available • Analyze watershed, including bedrock and surficial geology and morphometric screening • Conduct a site visit and qualitative assessment of the hazard without numerical modelling • Identify and map any very-low-hazard surfaces in the consultation area (e.g., inactive or relict depositional zones) • Consider watershed-scale environmental changes • Describe potential climate change effects (not typically quantified)	• A document describing the geomorphic setting and hazard zones • Descriptions of, designations for, and mapping of "safe" building sites • Description of siting constraints or protective measures, as required and under consideration of risk transfer	• Return period: 500 years • Time window: 250 years
1	• Possible loss of life even for single homes, urban developments • Types of projects: – Small subdivision: ▪ <5 single-family lots	• All that was completed for Class 0 • Employ methods to estimate frequency and magnitude, such as subsurface investigation and dendrochronology, where feasible and practical (subsurface investigation or exposures can identify processes and measure deposit thicknesses, and allow for radiometric dating) • Provide air photo interpretation of all available large-scale images • Estimate the frequency-magnitude (F-M) relationship • Map hazards • Perform a quantitative risk assessment (QRA) for probability of death of individuals (PDI) for each home; a group risk assessment is optional • Summarize projected temperature and precipitation changes and their potential effects on debris-flow processes • Assess climate change effects in terms of possible changes in the frequency and/or magnitude of the Landslide in question	• A report documenting all methods and results in the report or appendices • F-M model • Multicolour composite debris flow hazard map • PDI risk results tabulated by home address • Various risk-reduction options identified during the assessment, highlighting possible risk transfer, as required	• Return period: 1,000 years • Time window: 500 years
2	• Types of projects: – Medium to large subdivision: ▪ 6 to 50 single-family lots ▪ New subdivisions	• All that was completed for Class 1 • Complete numerical debris-flow runout modelling (2D or 3D) • Assess hazard cascades • Perform modelling-based hazard mapping of individual hazard scenarios, and create a composite hazard map • Quantify the effects of climate change on F-M and include the results in the QRA • Consider post-fire hazards • Conduct a group risk assessment (required)	• All that was provided for Class 1 • Individual hazard scenario maps and a composite hazard map • Descriptions of hazards beyond the fan boundaries	• Return period 2,500 years • Time window: 1,500 years

CLASS	APPLICATIONS	TYPICAL ASSESSMENT METHODS WITH CLIMATE CHANGE AND ENVIRONMENTAL CONSIDERATIONS	KEY DELIVERABLES	MINIMUM RETURN PERIOD & TYPICAL TIME WINDOW
3	• Types of projects: – Large to very large subdivisions (new towns and townships): ▪ >50 single-family lots ▪ New subdivisions	• All that was completed for Class 2 • Model and quantify a variety of hazard scenarios, including forced avulsions and auxiliary hazards associated with debris flows, such as off-fan flooding and erosion • Quantify the effects of climate change for two different emission scenarios (e.g., representative concentration pathway [RCP] of 4.5 and 8.5) at least to the year 2100, and include in the QRA • Quantify the post-fire hazard and include in the F-M model ensemble, where appropriate • Provide a detailed societal risk calculation (required)	• All that was provided for Class 2 • F-N plot of the group risk analysis results • Outcomes of the climate change effects analysis	• Return period: 5,000 years • Time window: 2,500 years

NOTES:

Abbreviations: F-M = frequency-magnitude; PDI = annual probability of death to an individual; QP = Qualified Professional; QRA = quantitative risk assessment

Table B - 3: Types of Risk Assessments for Rockfall and Rockslides

Note: The Qualified Professional (QP) can choose lower annual probabilities (higher return periods), where applicable.

CLASS	APPLICATIONS	TYPICAL ASSESSMENT METHODS WITH CLIMATE CHANGE AND ENVIRONMENTAL CONSIDERATIONS	KEY DELIVERABLES	MINIMUM RETURN PERIOD & TYPICAL TIME WINDOW
0	• Types of projects: – Renovations, expansions, new single houses, new duplexes	• Conduct a background review of grey and peer-reviewed literature; review legislated requirements • Provide air photo interpretation, where appropriate • Examine LiDAR information, if available • Analyze watershed, including bedrock and surficial geology and morphometric screening • Conduct a site visit and qualitative assessment of rockfall hazard through rockfall shadow zone delineation, using standard methodologies and field verification without numerical modelling • Identify and map any very-low-hazard zones in the consultation area • Consider watershed-scale environmental changes • Map boulder runout within the property footprint • Describe potential climate change effects (not typically quantified)	• A document describing the geomorphic setting and hazard zones • Descriptions of, designations for, and mapping of “safe” building sites • Description of siting constraints or protective measures, as required and under consideration of risk transfer	• Return period: 500 years • Time window: 250 years
1	• Possible loss of life even for single homes • Types of projects: – Scoping-level studies for linear infrastructures, mines, or urban developments – Small subdivisions: ▪ <5 single-family lots	• All that was completed for Class 0 • Conduct a site visit with site-specific terrain mapping, including the extent of source bluffs, talus top and toe, and farthest blocks beyond the toe • Identify hazard zones based on empirical shadow-zone, using standard methodologies and field verification. • Map rockfall hazards • Perform a quantitative risk assessment (QRA) for probability of death of individuals (PDI) for each Element at Risk; a group risk assessment is optional • Assess climate change effects in terms of possible changes in the frequency and/or magnitude of the Landslide in question	• A report documenting all methods and results in the report or appendices • Multicolour rockfall hazard map • PDI risk results tabulated by home address • Various risk-reduction options identified during the assessment, highlighting possible risk transfer, as required	• Return period: 1,000 years • Time window: 500 years
2	• Types of projects: – Medium to large subdivision: ▪ 6 to 50 single-family lots ▪ New subdivisions	• All that was completed for Class 1 • Perform a detailed kinematic analysis • Identify and date rockfall scars, with block-size distribution and delineation of farthest travelled blocks • Consider the effects of protective forests • Perform numerical rockfall runout modelling (1D, 2D, or 3D) • Perform modelling-based hazard mapping of individual rockfall hazard scenarios, and create a hazard map • Perform a QRA for probability of death of individuals (PDI) for each home; a group risk assessment is optional • Quantify climate change effects as much as possible, based on current understanding	• All that was provided for Class 1 • Individual hazard scenario maps and a composite hazard map • Descriptions of hazards beyond the fan boundaries	• Return period: 2,500 years • Time window: 1,500 years

CLASS	APPLICATIONS	TYPICAL ASSESSMENT METHODS WITH CLIMATE CHANGE AND ENVIRONMENTAL CONSIDERATIONS	KEY DELIVERABLES	MINIMUM RETURN PERIOD & TYPICAL TIME WINDOW
3	• Types of projects: – Large to very large subdivisions (new towns and townships): ▪ >50 single-family lots ▪ New subdivisions	• All that was completed for Class 2 • Model and quantify a variety of hazard scenarios and auxiliary hazards associated with rockfall, such potential creek damming • Provide a detailed societal risk calculation (required)	• All that was provided for Class 2 • F-N plot of the group risk analysis results	• Return period: 5,000 years • Time window: 2,500 years

NOTES:

Abbreviations: PDI = annual probability of death to an individual; QP = Qualified Professional; QRA = quantitative risk assessment

Table B - 4: Types of Risk Assessments for Rock Avalanches

Note: Rock avalanche repeat events at the same location are much rarer than other Landslide processes (see Tables B-2 and B-3). The Qualified Professional (QP) should therefore use the current slope activity and regional and nearby large-scale slope stability as a proxy for estimating future likelihood in X years of catastrophic detachment.

CLASS	APPLICATIONS	TYPICAL ASSESSMENT METHODS WITH CLIMATE CHANGE AND ENVIRONMENTAL CONSIDERATIONS	KEY DELIVERABLES	MINIMUM RETURN PERIOD & TYPICAL TIME WINDOW
0	• Very low potential for loss of life and low potential for economic losses • Types of projects: – Renovations, expansions, new single houses, new duplexes	• Conduct a background review of grey and peer-reviewed literature; review legislated requirements • Provide air photo interpretation, where appropriate • Examine LiDAR information, if available • Analyze watershed, including bedrock and surficial geology and morphometric screening • Conduct a site visit and empirical assessment of rock avalanche runout • Describe potential climate change effects (not typically quantified)	• A document describing the geomorphic setting and hazard zones • Descriptions of, designations for, and mapping of “safe” building sites. • Description of siting constraints or protective measures, as required and under consideration of risk transfer	• Return period: 500 years • Time window: 250 years
1	• Possible loss of life even for single homes • Types of projects: – Scoping-level studies for linear infrastructures, mines, urban developments – Small subdivisions: ▪ <10 single-family lots	• All that was completed for Class 0 • Conduct a source visit with site-specific terrain mapping, including the extent of source rock slopes • Rank the source zone by activity • Estimate source volume(s) • Identify hazard zones based on empirical runout-zone, using standard methodologies and field verification • Perform a quantitative risk assessment (QRA) for probability of death of individuals (PDI) for each home; a group risk assessment is optional • Assess climate change effects in terms of possible changes in the frequency and/or magnitude of the Landslide in question	• A report documenting all methods and results in the report or appendices • Multicolour rockfall hazard map • PDI risk results tabulated by home address • Various risk reduction options identified during the assessment, highlighting possible risk transfer, as required	• Return period: 1,000 years • Time window: 500 years
2	• Types of projects: – Medium to large subdivisions: ▪ 10 to 100 single-family lots ▪ New subdivisions	• All that was completed for Class 1 • Perform a detailed kinematic analysis • Perform numerical rock-avalanche runout modelling (2D or 3D) • Consider splash zones along rock avalanche margins • Consider river damming events and upstream and downstream flooding • Perform a QRA for probability of death of individuals (PDI) for each home; a group risk assessment is optional • Quantify climate change effects as much as possible, based on current understanding, with specific reference to changes in permafrost and glaciers, where present	• All that was provided in Class 1 • Individual hazard scenario maps and a composite hazard map, where appropriate • Descriptions of hazards beyond the impact zone boundaries	• Return period: 2,500 years • Time window: 1,500 years

CLASS	APPLICATIONS	TYPICAL ASSESSMENT METHODS WITH CLIMATE CHANGE AND ENVIRONMENTAL CONSIDERATIONS	KEY DELIVERABLES	MINIMUM RETURN PERIOD & TYPICAL TIME WINDOW
3	• Types of projects: – Large to very large subdivisions (new towns and townships): ▪ >100 single-family lots ▪ New subdivisions	• All that was completed for Class 2 • Model and quantify a variety of hazard scenarios and auxiliary hazards associated with rock avalanche, such as potential creek and river damming • Provide a detailed societal risk calculation (required)	• All that was provided for Class 2 • F-N plot of the group risk analysis results	• Return period: 5,000 years • Time window: 2,500 years

NOTES:

Abbreviations: PDI = annual probability of death to an individual; QP = Qualified Professional; QRA = quantitative risk assessment

Table B - 5: Types of Risk Assessments for Slumps and Spreads

CLASS	APPLICATIONS	TYPICAL ASSESSMENT METHODS WITH CLIMATE CHANGE AND ENVIRONMENTAL CONSIDERATIONS	KEY DELIVERABLES	MINIMUM RETURN PERIOD & TYPICALTIME WINDOW
0	• Low potential for loss of life due to slow deformation from Landslides, but could occur indirectly from ruptures and explosions of gas pipelines • Types of projects: – Renovations, expansions, new single houses, new duplexes • Applies only to proposed developments located downslope of the earthflow, unless it can be ascertained that the earthflow is relict	• Conduct a background review of grey and peer-reviewed literature; review legislated requirements • Examine local geology and geological history • Examine LiDAR information, if available • Conduct a site visit and qualitative assessment of the Landslide Hazard • Identify any very-low-hazard surfaces in the consultation area near competent bedrock ridges • Review air photos to determine morphologic changes • Describe potential climate change effects (not typically quantified)	• Document describing the geomorphic setting and hazard zones • Descriptions of, designations for, and mapping of "safe" building sites • Descriptions of siting constraints	• Return periods are not always applicable to slumps, spreads, and static liquefactions due to possible material depletion in those Landslide types • In case of repeat events (e.g., retrogressing slumps), the same annual probability applies as for other Landslide types
1	• Possible loss of life even for single homes or urban developments • Types of projects: – Small subdivision: ▪ <10 single-family lots	• All that was completed for Class 0 • Employ change detection methods (LiDAR or photogrammetry) to characterize average movement rates • Identify and qualify upstream mass movement processes or undercutting that could trigger creep accelerations • Employ drilling and borehole instrumentation to determine material characteristics • Perform a limit equilibrium analysis (2-D or 3D) • Identify the possibility of partial rapid mass movements • Use empirical runout tools to estimate runout for different Landslide types • Assess the effects of Landslide surface alterations	• A report including cross-sections and longitudinal sections with observed surface water, creep velocity, and qualitative description of recorded historic events • If significant watershed changes are detected, a determination of how this may affect watershed hydrology and connection to movement rates • Factor of Safety calculations • Hazard map based on movement rates	
2	• Types of projects: – Medium to large subdivisions: ▪ 10 to 100 single-family lots ▪ New subdivisions	• All that was completed for Class 1 • Document Landslide behaviour in a region with similar geology • Perform a simple time series analysis of climate data to examine if movement rates are related to climate • Review climate change predictions for the study region, and include the results in the assessment, if appropriate • Quantitative risk assessment (QRA) recommended • Perform a multivariate statistical analysis of climate data to predict movement rates	• All that was provided for Class 1 • Sections on engineering geology and climate data analysis • Presentation of QRA results	

CLASS	APPLICATIONS	TYPICAL ASSESSMENT METHODS WITH CLIMATE CHANGE AND ENVIRONMENTAL CONSIDERATIONS	KEY DELIVERABLES	MINIMUM RETURN PERIOD & TYPICALTIME WINDOW
3	• Types of projects: – Large to very large subdivisions (new towns and townships): ▪ >100 single-family lots ▪ New subdivisions	• All that was completed for Class 2 • Perform a failure mode analysis • Perform drilling through the Landslide and use radiometric dating to understand material characteristics and extrapolate movement rates • Employ borehole instrumentation with inclinometers and piezometers to understand depth of shear zone(s), phreatic surface oscillations, and pore water pressures • Perform a deterministic and probabilistic runout analysis in case sudden movement accelerations are expected • Complete runout modelling for different failure scenarios (2D or 3D) • Conduct a QRA (required)	• All that was provided for Class 2 • Summary of drilling results • Summary of material properties • Opinions on feasibility of Landslide stabilization	

NOTES:

Abbreviations: PDI = annual probability of death to an individual; QP = Qualified Professional; QRA = quantitative risk assessment

Table B - 6: Types of Static and Seismic Slope Stability Analysis

CLASS	APPLICATIONS	TYPICAL ASSESSMENT METHODS AND CLIMATE CHANGE AND ENVIRONMENTAL CONSIDERATIONS	KEY DELIVERABLES	MINIMUM RETURN PERIOD
0	• Temporary and short-term projects: – Individual Risk: very high potential for individual injury and/or life loss due to rapid collapse of a limited area with little or no warning – Very low group Risk • Low potential for property loss, but could occur indirectly through utility damage or foundation undermining • Low property-loss potential: – <$50,000 • Example projects: – Unsupported temporary excavation slopes: ▪ Short-term cut or fill slopes during Construction phases ▪ Period for temporary condition may range from hours up to 4 weeks – Supported temporary excavation slopes: ▪ Global static stability of system should be confirmed	• Conduct a site visit for a detailed geotechnical description of exposed soil profile and qualitative assessment of temporary slope stability • Identify potential destabilizing hazards in the consultation area, including heavy equipment and stockpile loading in study site vicinity • Identify weather triggers with potential to impact study site slopes (e.g., Environment Canada seasonal rainfall warning levels) • Climate change impacts not considered • QRA typically not required	• Memorandum report authenticated by an Engineering Professional per WorkSafe BC requirements, or by a Geoscience Professional (provided shoring design is not involved) • Static FS at least 1.3 • Seismic FS not typically considered	• Seismic loading conditions not considered due to short exposure period
1	• Property-scale slope instability: – Individual Risk: high potential for individual injury and/or life loss; failure warning signs may not be recognized by individual and/or rapid collapse could occur without warning – Group Risk will increase proportionally with affected population if Landslide is large enough to affect multiple properties • Moderate to high property-loss potential: – $0.1 million to $10 million • Example projects: – Building lots: ▪ Suitable building envelope for single-family dwelling ▪ Commercial buildings – Condominiums and townhomes	• Conduct a geotechnical hazard assessment study confirming intact soil slopes • Perform site exploration and in situ testing • Install piezometers and instrumentation where groundwater, semi-static water levels, and/or seepage conditions are anticipated within potential slope influence elevations • Conduct laboratory testing of retrieved samples • Conduct a site survey suitable for generation of slope sections • Perform slope stability analysis using appropriate limit equilibrium methods • Consider climate change impacts • QRA typically not required	• Geotechnical hazard assessment report with detailed study site plan and limit equilibrium slope stability analysis computer output • Static FS at least 1.5 • Seismic FS of 1.0 – Includes 15 cm adopted for determination of soil slope yield strength – The k_y is developed for an acceptable seismic FS = 1.0	• 1:2,475-year design earthquake for development • For BC MOTI bridges, structures, and embankments, seismic performance levels are based on importance classifications of Lifeline, Major-route, and Other for 1:2,475-year, 1:975-year, and 1:4,675-year design earthquakes, respectively

CLASS	APPLICATIONS	TYPICAL ASSESSMENT METHODS AND CLIMATE CHANGE AND ENVIRONMENTAL CONSIDERATIONS	KEY DELIVERABLES	MINIMUM RETURN PERIOD
2	• Subdivision-scale slope instability and/or post-disaster buildings that are designed to shelter people and/or remain functional in emergencies: – Group Risk will increase proportionally with affected population if Landslide is large enough to affect multiple properties • Very high property-loss potential: – $10 million to $100 million • Example projects: – Subdivisions: ▪ Residential lots ▪ Commercial or industrial – Post-disaster buildings ▪ e.g., schools, meeting halls, community facilities	• All that was completed for Class 1 • Complete additional detailed site characterization • Complete a Site-Specific Response Analysis (SSRA) • QRA may be required	• Detailed geotechnical report including a deformation map based on calculated slope movements • Static FS of at least 1.5 • Seismic FS determined specific to property • Tolerable deformation determined specific to property	• 1:2,475-year for development
3	• Community-scale instability and/or High Consequence structures with potential to affect people and properties beyond the limit of the Landslide: – Group Risk will increase proportionally with affected population if Landslide and structural failure impacts are large enough to affect multiple properties • Extreme economic loss potential: – >$100 million • Example projects: – Critical post-disaster facilities that must be functional or rapidly repairable after the design earthquake event ▪ e.g., nuclear facilities, selected dams, other high-Consequence scenarios	• All that was completed for Class 2 • Perform a failure mode and effects analysis • Perform a dynamic analysis using finite element or discrete element methods • QRA recommended • Conduct a site-specific hazard assessment (required) to determine very low probability seismic hazards (e.g., nuclear facilities, selected dams, other high-Consequence scenarios)	• All that was completed for Class 2, but with the findings of the deformation analysis • Presentation of QRA results	• 1:2,475-year or greater (e.g., BC Hydro dam safety targets of 1:10,000-year)

NOTES:

Abbreviations: BC MOTI = British Columbia Ministry of Transportation and Infrastructure; FS = Factor of Safety; QRA = quantitative risk assessment

B.3 DISCUSSION

The differences in return periods or annual probabilities considered for hazard and/or risk assessments are largely based on long-established methods; however, they may also be based on the practical limits of deciphering frequency-magnitude relationships, and the explicit understanding that estimating larger return period events may not be practicable, scientifically possible, or within reasonable confidence bounds. Furthermore, even if these conditions are met, the appropriate mitigation measures may not be affordable.

In this context, it is useful to compare return period ranges to those used in the Canadian Avalanche Association guidelines *Technical Aspects of Snow Avalanche Risk Management* (CAA 2016). The Canadian Avalanche Association considers return periods only up to 300 years; they typically do not estimate residual risk associated with greater return periods. There are multiple reasons for this decision, including that:

- avalanche events larger than those associated with a 300-year return-period class are typically not recorded or cannot be deciphered (since snow will melt, unlike rocks and soil) and the dendrochronological record from impact-scarred trees is limited by tree age;
- snow avalanches with higher return periods may not run out significantly further or be significantly larger, due to snow limitations and finite slab thickness (although there are cases where runout has been significantly beyond that of a 300-year return-period avalanche); and
- the uncertainty of estimating avalanches at higher return periods may reach the limits of credibility.

Strictly associating return periods with a specific Landslide Assessment scope and the related level of effort may not be possible. The reason is that even for a class 0 assessment, the QP may find that the lowest return period class of a specific Landslide process reaching the Element at Risk (e.g., a debris avalanche) may be 2,000 years. In that case, strict adherence to a minimum return period class of, for example, 500 years, may not be helpful, as it may lead to cases where the residual risk is ignored even when identified and quantified.

Therefore, the QP will need to decide which return periods to consider based on the context of the development proposal and the hazard and, in some cases, the minimum return periods for assessment provided by the Approving Authority. Specifically, if the results of the investigation reveal Landslide dates with a return period greater than the minimum return periods reported in Tables B-1 to B-6, the QP must report such a finding and qualify the incremental risk increase. The Approving Officer should then decide if the estimated risk is considered tolerable. Note that up to at least the minimum return periods in Tables B-1 to B-6 must be considered, but that does not mean lower or higher return periods can be ignored.

Irrespective of the decision about return periods, the QP must at least discuss the residual risk inherent in an assessment, even if larger return period Landslide types have not been considered. This will allow the Client and Approving Authority to understand the limitations of the analysis and aid in the decision making if there is merit in further residual risk reduction.

Return period estimates also need to consider nonstationarity in the analysis. Many factors introduce nonstationarity; for example, anthropogenic climate change, anthropogenic activities like site grading and water management that may affect stability, and changes in geomorphic rates associated with the paraglacial period (11,000 to 7,000 years BP), in which the effects of deglaciation led to a well-documented pulse of Landslide activity well beyond modern process rates (Church and Ryder 1972). This acknowledges nonlinearity in the time series, which can bias the notion of return period; as such, historical back-casting to estimate return periods is only reliable back to about 7,000 years ago, and even in that time period significant nonlinearity exists due to Holocene climate changes (Mathews et al. 2009). As is discussed in these guidelines under Section 3.4 Uncertainties, Limitations, and Qualifications of a Landslide Assessment, there are profound limitations and uncertainties in estimating very rare events.

In BC, the reference to the very remote 1:10,000-year hazard threshold has an historical context: It likely originates with a misinterpretation of the Supreme Court of British Columbia decision in *Cleveland Holdings Ltd. v. British Columbia (Department of Highways)*, [1973] B.C.J. No. 226 ("*Cleveland Holdings*"). Justice Berger's reference in *Cleveland Holdings* to 10,000 years was with respect to a sample time frame—the Holocene—and not as a hazard-based threshold. Further, it was a reference to group risk, judged to be "sufficient in the life of the community" but otherwise unspecified.

Assigning return periods to some Landslide processes, such as earth flows, slumps, or rock creep, particularly in soft rocks, may be difficult to achieve because the activity of those kinds of Landslides can only be differentiated in terms of changes in movement rates. In cases where such Landslides have been well monitored, and climate-movement rate statistical relationships may have been established, a probability of acceleration to a specific set of climate and weather factors could be established.

For creeping Landslide types (i.e., earthflows or soft rock creeps), the notion of return period does not apply, as those Landslides may always be in motion and could accelerate intermittently; therefore, a probability of Landslide velocity or displacement exceeding design criteria in 'n' years may be more appropriate. In addition, application of stringent deformation rates is not realistic, since over the Landslide surface there may be variation in deformation rates. For example, a building on a slab foundation may tolerate up to 100 mm/year of deformation if the entire building "floats" on the moving earth mass. Even then, differential settling can cause cracking in the building foundations. However, if the building straddles the margins of a Landslide, then shear through the building will quickly render the building uninhabitable even at rates of 10 mm/year or less (Mansour et al. 2011). Similarly, while deformation rates may be tolerable for buildings, nearby gas mains or water mains may be affected, whose leakage could either lead to explosions (from gas), environmental damage (from liquid hydrocarbons), or secondary Landslides (from water infiltration). Therefore, the decision as to what represents "tolerable" displacement rates will need to be site-specific and recognize the likely lifetime of a structure. Moreover, the displacement rate is only one relevant metric that helps in assessing the potential lifetime of a facility built on slowly moving Landslides. Equally important can be the cumulative displacement.

The QP needs to realize that there is always an unquantified residual risk if the F-M curve is truncated at some return period/annual probability level. Two questions emerge:

- First, could this truncation be detrimental to the outcome of the study?
- Second, how does a QP deal with unquantified risk?

Regarding the first question, most quantitative risk assessments conducted to date in BC indicate that for life-loss risk, the highest frequency of a geohazard resulting in one or more fatalities governs the risk, which means it has the highest incremental risk contribution. For example, imagine a rockslide threatens a development. A 1,000 m^3 rockslide with an assumed return period of 500 years would lead to 1.5 statistical deaths. The assessment also shows that a 5,000 m^3 rockslide could occur at a return period of 5,000 years, resulting in 4 statistical deaths. The former event results in a substantially higher risk due to the order of magnitude higher frequency. When calculating economic risk and annualizing, a similar result emerges. While there are some exceptions, the above-stated general rule prevails. Hence, given that mitigation funds are typically limited, the design event will, in most cases, become the highest frequency (smallest return period) event that leads to one or greater fatalities. Quantification of larger return period risks will thus have diminishing use as far as mitigation is concerned, and a truncation is warranted. This approach pertains to lower density developments but must be re-evaluated when higher density developments are proposed or already exist.

Following the *Cleveland Holdings* decision is the concern with high magnitude–low frequency events potentially affecting communities (e.g., rock avalanche). These events may be extremely destructive over large areas, and unmitigable other than by avoidance or early warning. In that case, the largest return period (minimum probability) should be considered. These cases warrant group risk assessment, and this involves a higher level of effort.

Regarding the second question, unquantified risk should be addressed by including in the report:

- an explicit description of the limitations of the study; and
- a brief description of unquantified risk items and their potential site relevance, including an explicit statement that such risks are not addressed by the study.

The increasing of the threshold return period with increasing exposure can be critiqued on the basis that, depending on the type of development, different individual risk values may be estimated for the same property, as in the following example:

- Consider a home at the bottom of a steep, debris-avalanche prone slope. If a major home renovation is required, Table B-2, class 0 applies, which stipulates that the QP ought to consider at least a 1:500-year annual probability (0.002). This may result in a risk of death of individuals (PDI) of $<10^{-5}$ (1:100,000), because the site in question is very unlikely to be reached for event scenarios up to, say, a 1:1,000-year annual probability, for which the QP can create a reasonably reliable frequency-magnitude relationship. In this case, the renovation is likely to be approved.
- In contrast, assume that the risk is being determined for the same home within the context of a new or existing development in which societal risk must be estimated and the F-M curve appropriately extended. Assuming that the development has more than 100 buildings, a class 3 level of effort in Table B-2 stipulates that the QP is required to establish a frequency-magnitude relationship to at least a 1:5,000-year annual probability. In this case, it may be determined that a debris avalanche could run to the property in question and the PDI risk would change.
- More importantly, in the context of community exposure, extending the F-M curve may lead to the result that societal risk affecting the proposed development (which includes the existing home) may be deemed intolerable. Thus, this problem of risk estimates varying by level of effort is partly a function of individual versus group risk (i.e., which risk metric is used for decision-making).

These issues may arise in existing developments created long before Landslide safety was integrated into development planning, but are largely avoidable in new development planning. In existing communities, where Approving Agencies are considering bylaws to allow densification, they should do so only after becoming well informed by group risk assessment.

In the case of a subdivision (existing or future), group life-loss risk estimates for rapid life-threatening Landslides, or economic risks for slow-moving Landslides will likely govern risk management decisions rather than PDI risk. The practice of assigning annual probabilities to the scale of development (i.e., exposed population) has a 30-year history in BC (Cave 1992, 1993), and to this date this method is applied in the Fraser Valley Regional District and elsewhere in BC (FVRD 2020). It also has many precedents worldwide for flood and Landslide management. Importantly, it is realized that it is neither reasonable nor logical to expect that either the Landowner or the QP require estimates of the full spectrum of hazard scenarios (up to and including a 1:10,000-year event) for small-scale developments or redevelopments. In many cases, full spectrum estimates are simply not reliably achievable with even substantial geoscientific effort, and are associated with very high uncertainties (and therefore subject to justified criticism). By including large return-period classes (with the noted exceptions), the incremental risk increase is usually so low that other everyday risks or other natural hazards (such as wildfires) may take a precedent over Landslide Risk. This is affirmed by the long-term statistics (1 to 2 per year) of life loss in BC due to Landslides (Strouth and McDougall 2021). Additionally, imposing those requirements may be cost-prohibitive.

It should be noted that the above issue is only pertinent to rapid Landslides of the flow- or fall-type (Tables B-2 and B-3), but does not apply to slow-moving Landslides or rock avalanches. In the latter case, the QP will need to estimate the probability of a rock slope to catastrophically fail sometime in the future, which is a function of the current degree of stability and/or activity encountered on the rockslide in question (Hermanns et al. 2012; Oppikofer et al. 2018).

B.4 REFERENCES – APPENDIX B

The following documents are referenced in Appendix B of these guidelines:

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APPENDIX C: REVIEW OF LEVELS OF LANDSLIDE SAFETY

As used in these guidelines, the term Level of Landslide Safety includes levels of acceptable Landslide Hazard and Landslide Risk.

Levels of Landslide Safety are determined by groups considering long-term collective interest, not individuals. Therefore, for a development affecting life safety, the levels must be established and adopted by the Local Government or the provincial government after consideration of a range of societal values. Some Landowners may feel a government-adopted Level of Landslide Safety is too high, while others are willing to live with what is considered an "unacceptable" Level of Landslide Safety.

Qualified Professionals (QPs) should not be expected to establish a Level of Landslide Safety, although they may provide a useful role in advising the Local Government or the provincial government in that regard.

The following subsections briefly review some aspects of Levels of Landslide Safety in Canada and specifically in British Columbia (BC).

C.1 CANADA

Canada does not have nationally adopted Levels of Landslide Safety. However, Landslide safety is addressed in federal codes and manuals.

C.1.1 NATIONAL BUILDING CODE OF CANADA

The *National Building Code of Canada 2015* (*NBC 2015*) does not specifically address Landslide safety, but it does include a statement from the *BC Building Code 2018* referring to Landslides:

- Where a foundation is to rest on, in, or near sloping ground, this particular condition shall be provided for in the design.

C.1.2 CANADIAN FOUNDATION ENGINEERING MANUAL

The *Canadian Foundation Engineering Manual 2006* (*CFEM 2006*) emphasizes foundation engineering, not Landslides; however, it does state the following regarding Landslide safety (Canadian Geotechnical Society 2006):

- The possibility of Landslides should always be considered, and it is best to avoid building in a Landslide area or potential Landslide area.
- When a potential Landslide area is identified, the area should be investigated thoroughly, and designs and Construction procedures should be adopted to improve the stability.

The *CFEM 2006* does not prescribe a Level of Landslide Safety; however, it does address limit equilibrium analysis and Factors of Safety (FS). Although limit state design is mandatory for foundation design (as per the *NBC 2015*), limit equilibrium analysis and FS still apply to Landslide analysis.

The *CFEM 2006* states the following regarding FS:

- FS reflect past experience under similar conditions.
- The greater the potential Consequences and/or the higher the uncertainty, the higher the design FS should be.
- Over time, similar FS have become common to geotechnical design throughout the world.

The *CFEM 2006* does not provide a range of FS that address Landslides specifically; however, based on data from Terzaghi and Peck (1996), the *CFEM 2006* indicates FS for earthworks (i.e., engineered fills) ranging from 1.3 to 1.5, and for unsupported excavations (i.e., engineered cuts) ranging from 1.5 to 2.0. The *CFEM 2006* indicates a lower FS may be acceptable:

- if a particularly detailed soil investigation has been carried out;
- where the analysis is supported by well-documented local experience;
- where geotechnical instrumentation to measure pore pressure and movement is provided and monitored at regular intervals to check the slope behaviour;
- where slope failure would have only limited Consequences; or
- if the Approving Authority has adopted a lower FS (i.e., the minimum FS of 1.3 for stabilized slopes used by the BC Ministry of Transportation and Infrastructure).

The *CFEM 2006* also addresses earthquake loading, and indicates the following:

- The *NBC 2015* has selected Ground Motions with a probability of exceedance of 2% in 50 years (annual probability of 1:2,475) for earthquake-resistant design purposes.
- The FS of a slope under static conditions must be significantly greater than 1.0 to accommodate earthquake loads.
- The acceptable FS depends on the uncertainty in the analysis, the soil parameters, and the magnitude and duration of seismic excitation, in addition to the potential Consequences of slope failure.

C.2 BRITISH COLUMBIA

Landslide safety is addressed in a number of provincial codes and other guidance that has been developed and referenced over the years. Following is a summary.

Note that the Province of BC continues to work on defining a Level of Landslide Safety that can be consistently applied across BC. Until a province-wide definition is available, QPs should refer to the Level of Landslide Safety that has been adopted by the local Approving Agency or another jurisdiction in BC (see subsection C.2.4 Engineers and Geoscientists BC Guidance).

C.2.1 SUPREME COURT OF BC DECISION IN *CLEVELAND HOLDINGS* (1973)

In *Cleveland Holdings Ltd. v. British Columbia (Department of Highways)*, [1973] B.C.J. No. 226 ("*Cleveland Holdings*"), Justice Berger upheld the Approving Officer's decision to refuse a subdivision as being against the public interest on the basis of the possibility of a major Landslide between Squamish and Whistler, BC presented an unacceptable risk to a proposed Residential Development. Justice Berger based his decision on the fact that experts believed there was a sufficient risk of catastrophic Landslide in the lifespan of the community.

The decision in *Cleveland Holdings* set a precedent for the application of Landslide Risk assessment in BC. The decision was subsequently used erroneously to imply a Level of Landslide Safety at an annual probability of occurrence, P(H)[10], of 1:10,000 (0.5% probability in 50 years) for a major Landslide affecting a community. In fact, in the reasons for decision in *Cleveland Holdings*, Justice Berger was referencing the sample time frame over which the catastrophic Landslide Hazard was assessed; that is, the approximately 10,000-year span of the Holocene.

[10] P(H) is an estimate of the annual probability of occurrence of a specific hazardous Landslide. P(H) is a measure of hazard, and not risk, because it does not consider the effects or potential effects of the Landslide on the proposed Residential Development (Wise et al. 2004).

C.2.2 BC MINISTRY OF TRANSPORTATION AND INFRASTRUCTURE

Sometime between 1978 and 1993, the BC Ministry of Transportation and Infrastructure (BC MOTI) began asking QPs who carried out Landslide Assessments for proposed subdivisions "to think in terms of a 10% probability in 50 years" (i.e., an annual probability of occurrence of 1:475, or a P(H) of 1:475) (BC MOTI 1993).

The BC MOTI online *Guide to Rural Subdivision Approvals*, Section 2.3.1.07, first published in 2005, and current to February 2021 (BC MOTI 2021) states that Engineering Professionals should:

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

The BC MOTI (2021) guide does not provide a Level of Landslide Safety other than the phrase "free from hazard," which, as noted previously, seldom applies. Note that although Geoscience Professionals are not included in that guide, they are included in the governing *Land Title Act*.

In the 1990s, as direction to the land-use planning studies being conducted for Cheekye fan, which is a large landform vulnerable to catastrophic Landslides within the District of Squamish, the Province of BC specified that a 1:10,000-year design event be considered (Sobkowicz et al. 1995). This direction was repeated in 2003 when a consultant was contracted to present a design for area-wide mitigation.

In 2009 and 2015, BC MOTI Approving Officers provided guidance in a document titled "Subdivision Preliminary Layout Review – Natural Hazard Risk." (As of the date of publication, this guidance document was not publicly available; contact a BC MOTI Approving Officer for further details.)

With respect to Landslides, Levels of Landslide Safety, that document stated the following:

- The Qualified Professional must distinguish between two different types of events: damaging events and life-threatening events.
  - When considering damaging events only, unless otherwise specified, a probability of occurrence of 1 in 475 years (10% probability in 50 years) for individual natural hazards should be used as a minimum standard.
  - Where the damaging event is a snow avalanche hazard, a probability of occurrence of 1 in 300 years should be used.
  - If life-threatening events or catastrophic events are identified as a potential natural hazard to a building lot, the Qualified Professional is to consider events having a probability of occurrence of 1 in 10,000 years (0.5% probability in 50 years) and is to identify areas beyond the influence of these extreme events.

C.2.3 BC BUILDING CODE

The *BC Building Code* (2018) contains in Division B Sentences 4.1.8.17.(1) and 9.4.4.4.(2) addressing site stability. The sentences are substantively identical and read:

- The potential for slope instability and its consequences, such as slope displacement, shall be evaluated based on site-specific material properties and ground motion parameters in Subsection 1.1.3 [Section 4.1.8.1 adds "as modified by Article 4.1.8.4] and shall be taken into account in the design of the structures and its foundations.

C.2.4 ENGINEERS AND GEOSCIENTISTS BC GUIDANCE

The Province of BC, with the support of Engineers and Geoscientists BC, is working on defining a Level of Landslide Safety that can be consistently applied across BC. Until a province-wide definition is available, QPs should refer to the Level of Landslide Safety adopted by the local Approving Agency or another jurisdiction in BC (e.g., Local Governments including the Fraser Valley Regional District, the District of North Vancouver, the District of Squamish, and the Cowichan Valley Regional District).

The QP could also provide the following (or a similar) statement in the Landslide Assessment Report as assurance:

> [*I, we, or the name of the firm*] estimate the annual probability of death to an individual is [*some value*]. The [*adopted or referenced*] level of landslide safety is [*some value*]. Therefore, as required by the *Land Title Act* or *Community Charter*, and using the above risk tolerance criteria as reference, in the professional opinion of [*name of the firm*], the land may be used safely for the use intended.

C.3 LOCAL GOVERNMENTS

In BC, a number of Local Governments, including those set out below, have defined life safety criteria for Landslides or other hazards in their communities.

See the Official Community Plan (OCP) and development permit application (DPA) policies for each community for details.

C.3.1 FRASER VALLEY REGIONAL DISTRICT

In the 1990s, what is now the Fraser Valley Regional District published adopted Levels of Landslide Safety for various types of natural hazards for a range of Residential Developments (Cave 1993).

These Levels of Landslide Safety, which are current today (FVRD 2020), were based on:

- a reinterpretation of the *Cleveland Holdings* (1973) Supreme Court of BC decision from "sufficient" catastrophic Landslide Risk within the 10,000-year-long post-glacial period into an unacceptable Landslide return period of 10,000 years for a proposed subdivision (that is, P(H) = 1:10,000);
- the 200-year return period for provincially sponsored flood-proofing[11]; and
- the BC MOTI (1993) guideline of 10% probability in 50 years (that is, P(H) = 1:475).

C.3.2 REGIONAL DISTRICT OF FRASER-FORT GEORGE AND THE DISTRICT OF KENT

In 1999, the Regional District of Fraser-Fort George and, similarly, the District of Kent adopted a Level of Landslide Safety following the BC MOTI (1993) guideline (that is, P(H) = 1:475).

[11] Although the processes of debris flows and debris floods overlap between Landslides and flooding, the provincial level of flooding safety (annual probability of 1:200) does not apply to debris flows or debris floods.

C.3.3 DISTRICT OF NORTH VANCOUVER

In 2009, the District of North Vancouver endorsed Individual risk and Factor of Safety criteria for Landslide safety in a report to their council titled "Natural Hazards Risk Tolerance Criteria" (District of North Vancouver 2009).

The criteria, which addresses natural hazards including Landslides, differentiates between existing developments and new developments, and sets more stringent Individual Risk criteria for new developments: 1:10,000 per annum for existing and 1:100,000 per annum for new. The Factor of Safety is set at 1.3 for static and 1.5 for seismic assessments.

C.3.4 DISTRICT OF SQUAMISH

In 2014, the District of Squamish commissioned an expert panel to review what hazard levels ought to be considered in land-use planning on Cheekye fan (Clague et al. 2014, 2015). They summarized past practice in BC (Table C - 1) and recommended that for the Cheekye fan, the 1:10,000-year debris flow "should be considered." They did not specify "must be considered," leaving room for QPs to determine, based on sound rationale, whether the specifics of a project merited such consideration.

Large subdivision proposals are being assessed in consideration of the 10,000-year event; while renovations or additions and reconstruction have recently been approved considering smaller more frequent events (e.g., 1:2,500-year).

In 2017, the District of Squamish adopted the District of North Vancouver policy in its DPA strategy for hazard lands.

C.3.5 VILLAGE OF LIONS BAY AND THE COWICHAN VALLEY REGIONAL DISTRICT

The Village of Lions Bay (2018) has considered life-safety policies that are less restrictive than the District of North Vancouver policy.

The Village of Lions Bay, in its draft Development Permit Area (DPA) guidelines, references 1:10,000 per annum plus ALARP[12] for a new development not requiring subdivision or rezoning and for a subdivision and/or rezoning to create four or fewer fee-simple or strata parcels (including the original parcel), and references 1:100,000 per annum only for subdivision and/or rezoning to create five or more fee-simple or strata parcels (including the original parcel).

However, at the time of publication, the Village of Lions Bay has not chosen to adopt the draft DPA guidelines, and continues to rely on Village staff and QP judgment to determine an appropriate Level of Landslide Safety for each project; staff refer QPs to the Cordilleran Report (Friele 2018), from which the draft guidelines were drawn. On some projects, QPs have referenced the draft DPA guidelines as a basis for determining an appropriate Level of Landslide Safety, however this is not mandatory and there is no assurance that use of the draft DPA guidelines in this manner will persist in the future.

The Cowichan Valley Regional District (2019) adopted life-safety policies that are less restrictive than the District of North Vancouver policy, referencing a life-safety risk threshold of 1:10,000-year plus ALARP for all proposed development.

[12] ALARP stands for "as low as reasonably practicable." The principal behind is that risk ought to be further lowered through structures, policies, warning systems, or other resiliency measures as long as the costs of those are not grossly disproportional to the achieved decreases in risk.

Table C - 1: Event Frequencies Used In Landslide Risk Assessments, Compiled By the Cheekeye Expert Panel [a]

EVENT FREQUENCIES USED IN GEORISK ASSESSMENT IN BRITISH COLUMBIA	RATIONALE
10,000-year return period event	• Rubble Creek (*Cleveland Holdings* 1973)[b] • Regional District of Fraser Valley (Cave 1993) • District of Squamish (2009) • BC Ministry of Transportation and Infrastructure (2015)
2,500-year return period event	• Engineers and Geoscientists BC (2018) (for debris flows and debris floods) • National Building Code of Canada (2005) (for earthquakes)
500-year return period event	• BC Ministry of Transportation and Infrastructure (2015)

NOTES:

[a] Table adapted from Clague et al. 2015.

[b] In *Cleveland Holdings Ltd. v. British Columbia (Department of Highways)*, [1973] B.C.J. No. 226, Justice Berger declined to reverse an Approving Officer decision to apply a 10,000- year (e.g., Holocene) sample time frame, not a return period event.

C.4 REFERENCES – APPENDIX C

The following documents are referenced in Appendix C of these guidelines:

BC Ministry of Transportation and Infrastructure (MOTI). 2021. Guide to Rural Subdivision Approvals. February 2021. Victoria, BC: Province of BC. [accessed: 2021 Dec 10]. https://www2.gov.bc.ca/assets/gov/driving-and-transportation/funding-engagement-permits/subdividing-land/rural_subdivision_guide.pdf.

BC MOTI. 2015. Subdivision Preliminary Layout Review – Natural Hazard Risk. [internal document]. Dated March 13, 2009; 2009, revised 2013 and 2015.

BC MOTI. 1993. Subdivision Policy and Procedures Manual. Systems Planning Research Officer. Victoria, BC: Province of BC.

Canadian Geotechnical Society. 2006. Canadian Foundation Engineering Manual (CFEM). Richmond, BC: Canadian Geotechnical Society.

Cave PW. 1993. Hazard Acceptability Thresholds for Development Approvals by Local Governments. In: Proceedings of Geological Hazards Workshop, University of Victoria, BC. February 20-21, 1991. BC Geological Survey Branch, Open File 1992-15. pp 15-26. Also available from the Regional District of Fraser Valley.

Clague JJ, Hungr O, Morgenstern NR, VanDine D. 2015. Cheekye River (Ch'kay Stak̲w) and Fan Landslide Risk Criteria. Prepared for Province of BC, Squamish Nation and its Partnership, District of Squamish. June 8, 2015. [accessed: 2021 Dec 10]. https://squamish.ca/assets/78deb9bc3e/Cheekye-Panel-2-Final-Report-JUne-6.pdf.

Clague JJ, Hungr O, VanDine DF. 2014. Report of the Cheekye River (Ch'kay Stakw) and Fan Expert Review Panel. Prepared for Province of BC, Squamish Nation, and District of Squamish, April 23, 2014, 49 pp.

District of North Vancouver. 2009. Risk Tolerance. Application of Risk Tolerance Criteria. [web page]. North Vancouver, BC: District of North Vancouver. [accessed: 2022 Feb 15]. https://www.dnv.org/programs-and-services/risk-tolerance.

District of Squamish. 2017. Official Community Plan, Bylaw 2100, Section 25 Hazard Lands, District of Squamish, BC.

Engineers and Geoscientists BC. 2018. Professional Practice Guidelines – Legislated Flood Assessments in a Changing Climate in BC. Version 2.1. Burnaby, BC: Engineers and Geoscientists BC. [accessed: 2021 Dec 10]. https://www.egbc.ca/app/Practice-Resources/Individual-Practice/Guidelines-Advisories.

Friele P. 2018. The Village of Lions Bay, Natural Hazards Development Permit Area Strategy: Coastal, Creek and Hillslope Hazards, Lions Bay, BC, Canada. Final Version 4, dated January 18, 2018. Report prepared by Cordilleran Geoscience for the Village of Lions Bay. [accessed: 2022 Sep 08]. https://www.lionsbay.ca/sites/2/files/docs/services/Planning/02_pierre_friele_-_lions_bay_dpa_final_v4maps.pdf.

Sobkowicz J, Hungr O, Morgan G. 1995. Probabilistic Mapping of a Debris Flow Hazard Area: Cheekye Fan, British Columbia. In: Proceedings of the 48th Canadian Geotechnical Conference. pp. 519-529.

Terzaghi K, Peck RP. 1996. Soil Mechanics in Engineering Practice. Third Edition. New York, NY: Wiley.

Wise MP, Moore GD, VanDine DF (editors). 2004. Landslide Risk Case Studies in Forest Development Planning and Operations. BC Ministry of Forests, Land Management Handbook 56. Victoria, BC: Government of BC. [accessed: 2022 Jan 25]. https://www.for.gov.bc.ca/hfd/pubs/Docs/Lmh/Lmh56.htm.

APPENDIX D: LANDSLIDE ASSESSMENT ASSURANCE STATEMENT

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LANDSLIDE ASSESSMENT ASSURANCE STATEMENT

Notes: This statement is to be read and completed in conjunction with the Engineers and Geoscientists BC *Professional Practice Guidelines – Landslide Assessments in British Columbia* ("the guidelines") and the current *BC Building Code* (*BCBC*), and is to be provided for Landslide Assessments (not floods or flood controls), particularly those produced for the purposes of the *Land Title Act*, *Community Charter*, or *Local Government Act*. Some jurisdictions (e.g., the Fraser Valley Regional District or the Cowichan Valley Regional District) have developed more comprehensive assurance statements in collaboration with Engineers and Geoscientists BC. Where those exist, the Qualified Professional is to fill out the local version only. Defined terms are capitalized; see the Defined Terms section of the guidelines for definitions.

To: The Approving Authority (or Client) Date: ______________________________

____

____

Jurisdiction/name and address

With reference to (CHECK ONE):

- ☐ A. *Land Title Act* (Section 86) – Subdivision Approval
- ☐ B. *Local Government Act* (Sections 919.1 and 920) – Development Permit
- ☐ C. Community Charter (Section 56) – Building Permit
- ☐ D. Non-legislated assessment

For the following property (the "Property"):

____

Civic address of the Property

The undersigned hereby gives assurance that they are a Qualified Professional and a professional engineer or professional geoscientist who fulfils the education, training, and experience requirements as outlined in the guidelines.

I have signed, authenticated, and dated, and thereby certified, the attached Landslide Assessment Report on the Property in accordance with the guidelines. That report must be read in conjunction this statement.

In preparing that report I have:

[CHECK TO THE LEFT OF APPLICABLE ITEMS]

___ 1. Collected and reviewed appropriate background information
___ 2. Reviewed the proposed Residential Development or other development on the Property
___ 3. Conducted field work on and, if required, beyond the Property
___ 4. Reported on the results of the field work on and, if required, beyond the Property
___ 5. Considered any changed conditions on and, if required, beyond the Property
6. For a Landslide Hazard analysis or Landslide Risk analysis, I have:
___ 6.1 reviewed and characterized, if appropriate, any Landslide that may affect the Property
___ 6.2 estimated the Landslide Hazard
___ 6.3 identified existing and anticipated future Elements at Risk on and, if required, beyond the Property
___ 6.4 estimated the potential Consequences to those Elements at Risk
7. Where the Approving Authority has adopted a Level of Landslide Safety, I have:
___ 7.1 compared the Level of Landslide Safety adopted by the Approving Authority with the findings of my investigation
___ 7.2 made a finding on the Level of Landslide Safety on the Property based on the comparison
___ 7.3 made recommendations to reduce Landslide Hazards and/or Landslide Risks

8. Where the Approving Authority has **not** adopted a Level of Landslide Safety, or where the Landslide Assessment is not produced in response to a legislated requirement, I have:
   ___ 8.1 described the method of Landslide Hazard analysis or Landslide Risk analysis used
   ___ 8.2 referred to an appropriate and identified provincial, national, or international guideline for Level of Landslide Safety
   ___ 8.3 compared those guidelines (per item 8.2) with the findings of my investigation
   ___ 8.4 made a finding on the Level of Landslide Safety on the Property based on the comparison
   ___ 8.5 made recommendations to reduce Landslide Hazards and/or Landslide Risks

___ 9. Reported on the requirements for future inspections of the Property and recommended who should conduct those inspections

Based on my comparison between:

[CHECK ONE]

☐ the findings from the investigation and the adopted Level of Landslide Safety (item 7.2 above)
☐ the appropriate and identified provincial, national, or international guideline for Level of Landslide Safety (item 8.4 above)

Where the Landslide Assessment is not produced in response to a legislated requirement, I hereby give my assurance that, based on the conditions[1] contained in the attached Landslide Assessment Report:

A. SUBDIVISION APPROVAL

☐ For subdivision approval, as required by the *Land Title Act* (Section 86), "the land may be used safely for the use intended"
[CHECK ONE]
   ☐ with one or more recommended additional registered Covenants
   ☐ without an additional registered Covenant(s)

B. DEVELOPMENT PERMIT

☐ For a development permit, as required by the *Local Government Act* (Sections 488 and 491), my report will "assist the local government in determining what conditions or requirements it will impose under subsection (2) of [Section 491]"
[CHECK ONE]
   ☐ with one or more recommended additional registered Covenants
   ☐ without an additional registered Covenant(s)

C. BUILDING PERMIT

☐ For a building permit, as required by the *Community Charter* (Section 56), "the land may be used safely for the use intended"
[CHECK ONE]
   ☐ with one or more recommended additional registered Covenants
   ☐ without any additional registered Covenant(s)

---

[1] When seismic slope stability assessments are involved, Level of Landslide Safety is considered to be a "life safety" criteria, as described in Commentary JJJ of the *National Building Code of Canada* (*NBC) 2015*, Structural Commentaries (User's Guide – NBC 2015: part 4 of division B). This states:

> "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), 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."

LANDSLIDE ASSESSMENT ASSURANCE STATEMENT

____
Name (print)

____
Date

____
Address

____

____
Telephone

____
Email

(Affix PROFESSIONAL SEAL and signature here)

The Qualified Professional, as a registrant on the roster of a registrant firm, must complete the following:

I am a member of the firm _______________________________
(Print name of firm)

with Permit to Practice Number _______________________________
(Print permit to practice number)

and I sign this letter on behalf of the firm.

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APPENDIX E: METHODS OF SEISMIC ANALYSIS OF SOIL SLOPES

E.1 INTRODUCTION

As discussed in Section 1.0 Introduction, over 10 years have passed since the last revision of these guidelines, so an update of existing methods in the seismic analysis of soils slopes is warranted.

The impetus for the previous revision of these guidelines in 2010 was the publication of the *BC Building Code (BCBC) 2006*. The *BCBC 2006* adopted the Ground Motions for seismic design as stated in the *National Building Code of Canada* (*NBC*) *2005*. Those Ground Motions have a probability of exceedance of 2% in 50 years (annual probability of exceedance of 1:2,475), whereas the previously adopted Ground Motions for seismic design (*NBC 1995*, *BCBC 1998*) had a probability of exceedance of 10% in 50 years (annual probability of exceedance of 1:475). The effect of this change was to increase the number of slopes that could be considered unstable during an earthquake and therefore potentially unsuitable for Residential Development.

For this current revision of these guidelines, the *BCBC 2018* is used, which adopted the Geological Survey of Canada (GSC) fifth-generation ground-motion model, as stated in the *NBC 2015*. Some key changes impacting projects in British Columbia (BC) include:

- probabilistic treatment of the Cascadia subduction zone;
- reconfigured seismic source zones based on new data;
- explicit definition of crustal fault zones in the Yukon and offshore western Canada;
- improved magnitude-frequency statistics; and
- adoption of a suite of representative backbone ground-motion models.

A sixth-generation model is proposed by the GSC for the *NBC 2020*. Anticipated key changes that will impact projects in BC include:

- refinements to computed seismic hazard values, using the OpenQuake engine software;
- addition of peak ground velocity (PGV) in calculated output for use in damage assessment;
- addition of four rupture earthquakes to the Cascadia subduction zone;
- refinement of the inslab seismicity sources for the Georgia Strait/Puget Sound (GTP) zone;
- addition of two new fault zones near Victoria, BC; and
- direct calculation of hazard for each site class (i.e., loss of Site Class C as a reference hazard calculation class).

To prepare the previous revision in 2010, Engineers and Geoscientists BC, with support from the provincial government, established the Task Force on Seismic Slope Stability (TFSSS) to study the issue of seismic slope stability and make appropriate recommendations. The TFSSS reviewed practice current at the time, and recent developments in seismic analysis of soil slopes until then, and recommended two new methods of analysis based on the concept of tolerable earthquake-induced slope displacements along a slip surface.

These methods were intended for soil slopes, primarily where the location of the proposed residential building is at the top of the slope. Where a building is at the toe of the slope, and the hazard area includes soil or rock slopes above, then seismic slope stability analysis of those upper slopes would not be appropriate. In that case, mapping and other methods to characterize credible hazards would be applied.

Ongoing research, along with substantial additional Ground Motion data collected since the 2010 revision by TFSSS contributors Dr. Bray, Dr. Macedo, Dr. Travasarou, and others, has resulted in some additional refinement of the methods.

For the current revision of these guidelines, the updated methods identified in this appendix are suitable for application to both proposed Residential Developments and other developments, including institutional, commercial, industrial, and infrastructure projects, when combined with an appropriate limiting displacement and reference seismic hazard level.

These updated methods provide a sense of seismically induced displacement that may be expected for a given slope configuration, and are intended to aid practitioners in deciding whether to proceed with performance-based assessment or more advanced analysis efforts (i.e. additional site characterization or dynamic analysis).

E.2 REVIEW OF CURRENT PRACTICE

In BC, the common method used to carry out seismic slope stability analysis of soil slopes is constant horizontal force, expressed as kW, applied to the centre of gravity of the potential sliding mass, where W is the weight of the sliding mass and k is a seismic coefficient expressed as a proportion of peak ground acceleration (PGA). This method is depicted in Figure E - 1.

For the 2010 revision, the TFSSS found that seismic coefficients used by practitioners in BC could range from 0.5(PGA) ≤ k ≤ 1.0(PGA). The choice of k = 1.0(PGA) is generally very conservative and should only be used as a screening value. If the Factor of Safety (FS) ≥ 1, when k = 1.0(PGA) is used in a pseudo-static limit equilibrium slope stability analysis, no further stability analyses are required. This remains unchanged in this current revision.

Methods developed by the TFSSS built on determinations of seismic slope stability by Newmark in the mid-1960's (i.e., the rigid sliding block model) (Newmark 1965). Newmark determined that permanent slope displacement occurs during an earthquake only if the shear stresses generated by the earthquake exceed the shearing resistance of the soil. The horizontal force required to bring the slope to the condition of incipient slope displacement is expressed as k_yW, where W is the weight of the sliding mass, and k_y is the seismic yield coefficient—a special value of the seismic coefficient that just allows slip or yielding in the slope. The seismic yield coefficient is expressed as a_y/g, where, a_y is the yield acceleration and g is the acceleration due to gravity.

Slope displacements will be initiated whenever the ground acceleration, "a", exceeds the yield acceleration, as shown in Figure E - 2. The total slope displacement at the end of earthquake shaking is the sum of the incremental slope displacements generated each time the ground acceleration exceeds the yield acceleration.

The TFSSS reviewed recent developments in methods of seismic slope analysis of soil slopes, and selected a new approach based on the concept of tolerable slope displacement. The method was based on the work of Bray and Travasarou (2007), and is summarized below.

Travasarou's equation for estimating non-zero slope displacements along the slip surface greater than 1 cm was expressed as follows (note that this equation is valid for periods, T_s, in the range 0.05 s < T_s < 2.0 s, and for values of yield coefficient, k_y, in the range 0.01 < k_y < 0.5):

$$ln(D) = -1.10 - 2.83\,ln(k_y) - 0.333\left(ln(k_y)\right)^2 + 0.566\,ln(k_y)\,ln(S(T)) + 3.04\,ln(S(T)) - 0.244\left(ln(S(T))\right)^2 + 1.5T_s + 0.278\,(M\text{-}7), \quad [1]$$

where D is the median displacement in centimetres (cm) with a conditional probability of exceedance of 50%, if an earthquake occurs such that probability of the median slope displacement being exceeded is only 1% in 50 years (approximate annual probability of 1:5,000);

k_y is the seismic yield coefficient (best determined by iterative analyses using commercially available slope stability computer programs), which, because k_y is assumed to be a constant during earthquake shaking, is used only for cases where the soil forming the slope does not undergo significant strength loss (i.e., non-liquefiable or not susceptible to cyclic mobility);

M is the moment magnitude of the design earthquake (de-aggregation with modal magnitude values for BC are available from Earthquakes Canada); and

T is the degraded period of the sliding mass, in seconds(s), adjusted for the effects of strong shaking, given by $T = 1.5\ T_s$, where T_s is the initial fundamental period of the potential sliding mass, in seconds (s), prior to the design seismic event.

For typical slope configurations, estimations of T_s can be calculated as shown in Figure E - 3, Equation 2, where H is the average height and V_s is the average shear wave velocity in metres per second (m/s), of the potential sliding mass. For sliding along the base, H is the height of the slope. For other sliding surfaces, such as circular, the height is the estimated average depth of the sliding mass.

S(T) is the spectral response acceleration of the slope, in units of gravity (g), for the degraded slope period of $1.5T_s$. S(T) is given by the following equation:

$$S(T) = F * S_a(1.5T_s), \qquad [3]$$

where F is the amplification or de-amplification factor for the site class of the ground below the slope; and

$S_a(1.5T_s)$ is the 5% damped spectral response acceleration at the site for the reference ground conditions.

Values of S_a for periods of 0.0(PGA), 0.2, 0.5, 1.0, and 2.0 seconds (s) for a 2% probability of exceedance in 50 years were given in the *BCBC 2006*, Division B, Appendix C (also available from Earthquakes Canada). The greater value of F_a or F_v were used for F.

The TFSSS proposed 15 cm or less as a tolerable slope displacement along the slip surface for use with the Bray and Travasarou (2007) method for most cases and with a fundamental objective to avoid the slip surface "daylighting" within, or behind (landward of), the building.

A further simplification adopted by the TFSSS provided for a single equation to calculate a seismic coefficient, k_{15}, that would be compatible with 15 cm of slope displacement along the slip surface, as shown in the following equation:

$$k_{15} \sim (0.006 + 0.038\ M) * S(0.5) - 0.026; \quad S < 1.5\ g, \qquad [4]$$

where M is the moment magnitude of the modal earthquake; and

S(0.5) is the spectral response acceleration for a degraded period of 0.5 s.

Note that equation 4 is valid only for S(0.5) and should not be used with slope-specific periods that differ substantially from the representative spectral period of 0.33 s.

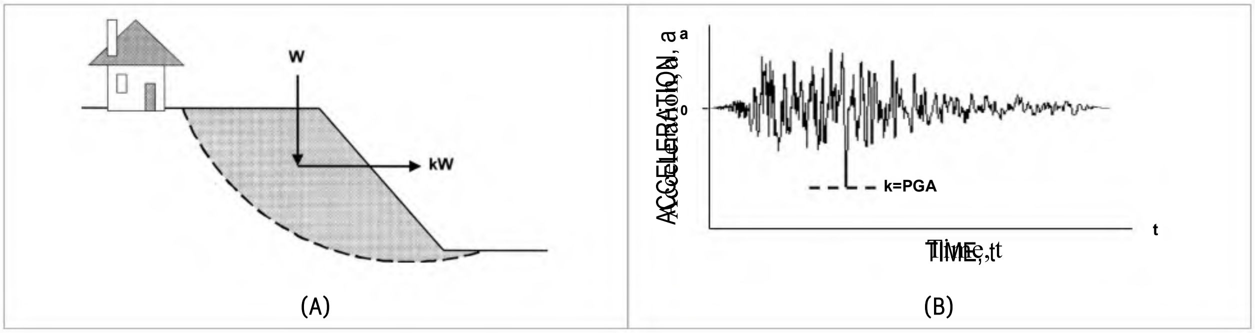


Figure E - 1: Illustration of the (A) pseudo-static limit equilibrium method of seismic slope stability analysis with a constant horizontal force, kW; and (B) ground shaking record showing k = 1.0(PGA) can be overly conservative

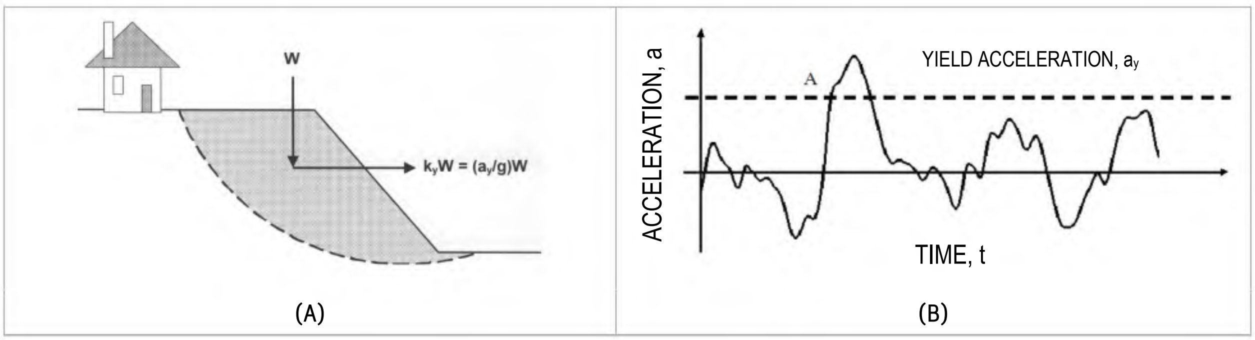
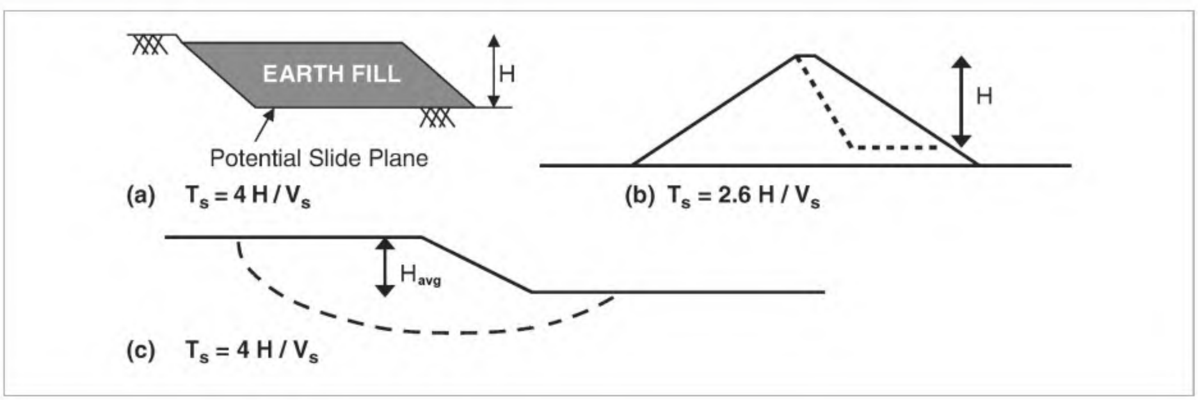


Figure E - 2: Illustration of the (A) pseudo-static limit equilibrium method of seismic slope stability analysis showing the condition of incipient slope displacement; and (B) expanded earthquake record showing yield acceleration



[2]

Figure E - 3: Illustration of the equation for estimation of the fundamental period of potential sliding masses

NOTE: Adapted from Bray (2007)

E.3 SLOPE PERFORMANCE DURING EARTHQUAKE SHAKING

DISCLAIMERS

1. In the evaluation of the seismic performance of a natural soil slope, the Qualified Professional (QP) should first assess if there are subsurface conditions considered likely to lose significant strength as a result of cyclic loading (e.g., soil liquefaction for non-cohesive soils or cyclic mobility for cohesive soils). For these cases, large displacement flow slides are possible, and they are not covered by calculation methods presented in this appendix. A brief discussion of liquefiable sites is provided in subsection E-5 Liquefaction Displacement Assessments.
2. In the analysis of natural soil slopes under static and seismic loading conditions in this appendix, it is imperative that the QP completely understands the characteristics of the study site slope that includes confirmation that the slope is in "intact" condition (i.e., no history of slope creep or post-depositional Landslide activity). The most detailed slope stability analysis can end up being meaningless if the slope is poorly understood, resulting in estimated soil-strength characteristics that are unconservative (i.e., actual soil strength in post-peak or residual shear strength condition), or a failure to identify the presence of an existing and foreseeable low-strength rupture surface or surfaces.

Additional research efforts by Bray et al. (2018), Macedo et al. (2018), and Bray and Macedo (2019) have further refined methods for the seismic stability analysis of soil slopes recommended in the previous 2010 revision of these guidelines.

The following summarizes refinements to the methods reflected in this current revision:

- The updated procedure utilizes 6,711 two-component horizontal Ground Motion recordings versus 688 recordings in Bray and Travasarou (2007).
- Procedures have been developed for shallow crustal zone and deep subduction zone interface earthquakes.
- The full coupled sliding block model from Bray and Travasarou (2007) has been modified, using more stable analytical methods developed by Chopra and Zhang (1991).
- The threshold of negligible displacement has been reduced from $d_0 = 1$ cm to $d_0 = 0.5$ cm;
- The 5%-damped spectral acceleration at the degraded (lengthened) period of the sliding mass has been revised to $S_a(1.3T_s)$ from $S_a(1.5T_s)$ for shallow crustal zone earthquakes.
- Two equations were developed to consider resonance of the sliding mass at a practical resonance condition, where $T_s = 0.7$ s for predicted probability of zero displacement ($D \leq 0.5$ cm)
- The updated methods require the QP to confirm that the reference Ground Motion at the base of the study slope is appropriate for the site conditions. In some cases, Site-Specific Response Analysis may be required to determine appropriate input Ground Motions.

For this current revision, work by the TFSSS for the 2010 revision was updated to reflect advances identified by selected TFSSS researchers since then, and current seismic hazard calculations by the GSC were added.

The following sections summarize advancements in the process based on the findings of additional study by Bray and others. In addition, analysis methods are presented to demonstrate decision steps in the analytical process for estimating shear-induced and volumetric-induced slope displacements for ordinary Ground Motions due to shallow crustal zone earthquakes and deep subduction zone interface earthquakes, and for estimating several types of displacement.

E.3.1 DISPLACEMENT FROM SHALLOW CRUSTAL ZONE EARTHQUAKES

An approximate response boundary between rigid slopes and flexible slopes has been adopted by researchers as the natural slope period $T_s = 1$ s. An illustration from Rathje and Antonakos (2011) is shown in Figure E - 4.

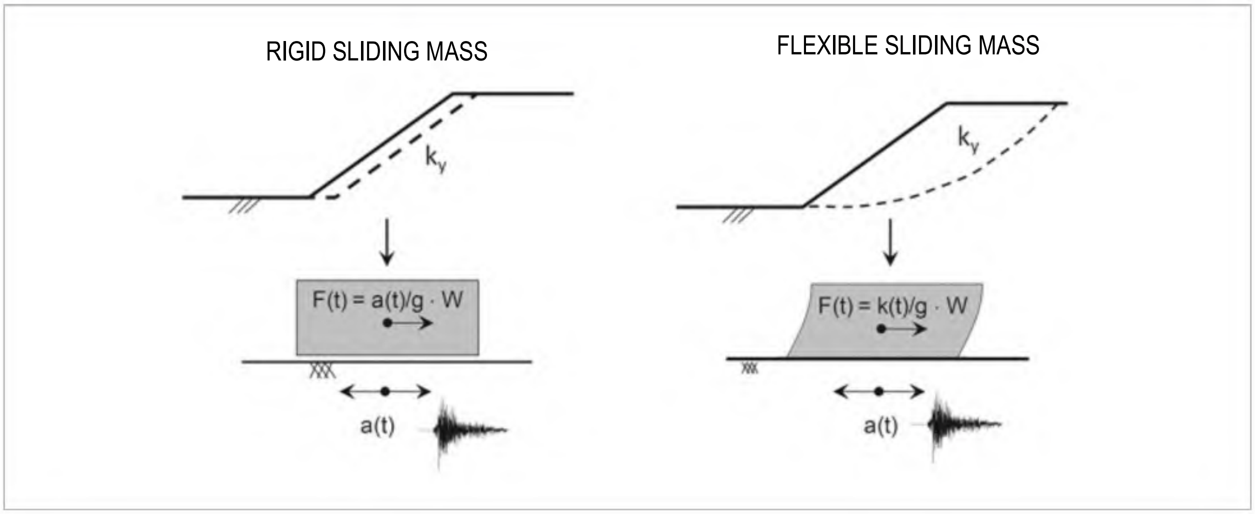


Figure E - 4: Illustration of rigid and flexible models for earthquake-induced sliding masses

NOTE: Adapted from Rathje and Antonakos (2011).

a) Stiff Slopes: Rigid Sliding Block Displacements

Tolerable slope displacements (D) for shallow sliding are represented by a stiff slope (i.e., the Newmark rigid block model) with an assumed slope period (T_s) of approximately zero seconds.

Slope displacements are calculated by Bray and Macedo with the following equation:

$$ln(D) = -4.684 - 2.482\, ln(k_y) - 0.244\, \left(ln(k_y)\right)^2 + 0.344\, ln(k_y)\, ln(PGA) + 2.649\, ln(PGA) - 0.909\, \left(ln(PGA)\right)^2 + 0.603\,(M), \quad [5]$$

where PGA is peak ground acceleration (g) adjusted for topographic effects, as presented above (see subsection E.2 Review of Current Practice); and

D is the median displacement, K_y is the seismic yield coefficient, and M is the moment magnitude of the design earthquake, as defined previously (see subsection E.2 Review of Current Practice).

For shallow translational-type slope movements, topographic effects should consider earthquake motion input. Shallow translational sliding mode can be expected to occur in steep slopes near slope crest areas, or in slopes where a shallow approximately slope-parallel contrast in soil strength conditions exists (e.g., steep colluvium soils overlying shallow depth to glacial soil, bedrock slopes, or landfill liners).

To capture topographic amplification effects for shallow localized sliding, the following PGA factors are recommended (Bray and Macedo 2019):

- *Tlt* for topographic factoring of
  - 1.3(PGA) for moderate slopes <60 degrees, and
  - 1.5(PGA) for steep slopes >60 degrees (Ashford and Sitar 2002).

Long or full slope shallow sliding masses on moderate slopes tend to produce lateral incoherence of ground shaking, such that a PGA reduction should be considered as follows:

- *Tfs* for topographic factoring of
  - 0.65(PGA) for long moderate slopes (i.e., <60 degrees).

b) Flexible Slopes: Shear-Induced Displacements

Bray and Macedo (2019) conducted additional fully coupled nonlinear deformable stick-slip type slope displacement analyses to update the Bray and Travasarou (2007) procedure, using 6,711 shallow crustal two-component recorded Ground Motions obtained from the new NGA-West 2 database compiled by the Pacific Earthquake Engineering Research Center (PEER 2013).

From a regression analysis of the resulting slope displacements, Bray and Macedo developed equations to estimate the magnitude of slope displacement due to shearing of the soil along a slip surface for ordinary Ground Motions.

The equation for estimating non-zero slope displacements along the slip surface (D > 0.5 cm) under ordinary Ground Motion is expressed as follows (note that this equation is valid for periods, T_s, in the range 0.10 s < T_s < 2.0 s, and for values of yield coefficient, k_y, in the range 0.01 < k_y < 0.5):

$$\begin{aligned} ln(D) = & -5.981 - 2.482\, ln(k_y) - 0.244\left(ln(k_y)\right)^2 \\ & + 0.344\, ln(k_y)\, ln(S(T)) + 2.649\, ln(S(T)) \\ & - 0.090\left(ln(S(T))\right)^2 + 3.152\,(T_s) - 0.945(T_s)^2 \\ & + 0.607\,(M), \end{aligned} \quad [6]$$

where D is the median displacement, k_y is the seismic yield coefficient, and M is the moment magnitude of the design earthquake, as defined previously (see E.2 Review of Current Practice); and

T is the degraded period of the sliding mass, in seconds(s), adjusted for the effects of strong shaking, and given by $T = 1.3T_s$, where T_s is the initial fundamental period of the potential sliding mass, in seconds (s), prior to the design seismic event.

Bray and Macedo also developed equations for shallow fault systems using pulse motion earthquake database information (i.e., large PGV oriented generally in the fault-normal direction). However, in BC, estimation of seismic slopes displacements that may be caused by near-fault pulse Ground Motions may not be feasible at this time, based on current limited understanding of potentially active shallow fault systems in the Lower Mainland and throughout BC.

E.3.2 DISPLACEMENT FROM DEEP SUBDUCTION EARTHQUAKES

Bray et al. (2018) conducted additional fully coupled nonlinear deformable stick-slip type slope displacement analyses, using 810 Ground Motion records selected from earthquakes with moment magnitude >M7 compiled from the Pacific Earthquake Engineering Research Center (PEER) and Central America databases. From a regression analysis of the resulting slope displacements, they developed equations to estimate the magnitude of slope displacement due to shearing of the soil along a slip surface for the selected Ground Motions. Updated methods were validated by comparing findings to earlier study (Bray and Travasarou 2007).

The Bray et al. (2018) equation for estimating slope displacements along the slip surface greater than 0.5 cm, and for most practical cases, is expressed in the following equation (note that this equation is valid for periods, T_s, in the range 0.10 s < T_s < 2.0 s, and for values of yield coefficient, k_y, in the range 0.01 < k_y < 0.5):

$$\begin{aligned} ln(D) = & -6.896 - 3.353\, ln(k_y) - 0.390\left(ln(k_y)\right)^2 \\ & + 0.538\, ln(k_y)\, ln(S(T)) + 3.060\, ln(S(T)) \\ & - 0.225\left(ln(S(T))\right)^2 + 3.081\,(T_s) - 0.803\,(T_s)^2 \\ & + 0.550\,(M), \end{aligned} \quad [7]$$

where D is the median displacement, k_y is the seismic yield coefficient, and M is the moment magnitude of the design earthquake, as defined previously (see E.2 Review of Current Practice); and

T is the degraded period of the sliding mass, in seconds (s), adjusted for the effects of strong shaking and given by $T = 1.5\ T_s$, where T_s is the initial fundamental period of the potential sliding mass, in seconds (s), prior to the design seismic event.

E.3.3 PROBABILISTIC APPROACH FOR DISPLACEMENT HAZARD CURVES

The GSC's fifth-generation seismic hazard calculations (NRC 2021a), available online, are now fully probabilistic and include seismic hazards from the Cascadia subduction earthquake to generate uniform hazard spectra (UHS).

This introduces an additional challenge to the simple seismic slope displacement determinations described above, in that three earthquake zones (crustal, inslab, and interface) are represented in the UHS. Crustal and inslab earthquake zones (approximately M7) and the interface or subduction zone (approximately M9) represent a substantially different contribution of potential energy to the UHS (see Figure E - 5). Use of the seismic hazard calculations for the combination of all earthquake sources, and the seismic slope displacement method for interface earthquakes, overestimates displacement. Therefore, a probabilistic method is required to determine seismic slope displacement from each earthquake zone contributing to the hazard at a specified response spectral acceleration.

A probabilistic method developed by Wu (2017) provides a rational approach for combining seismic slope displacements using the hazard spectra for crustal, inslab, and interface sources published by Halchuk et al. (2016).

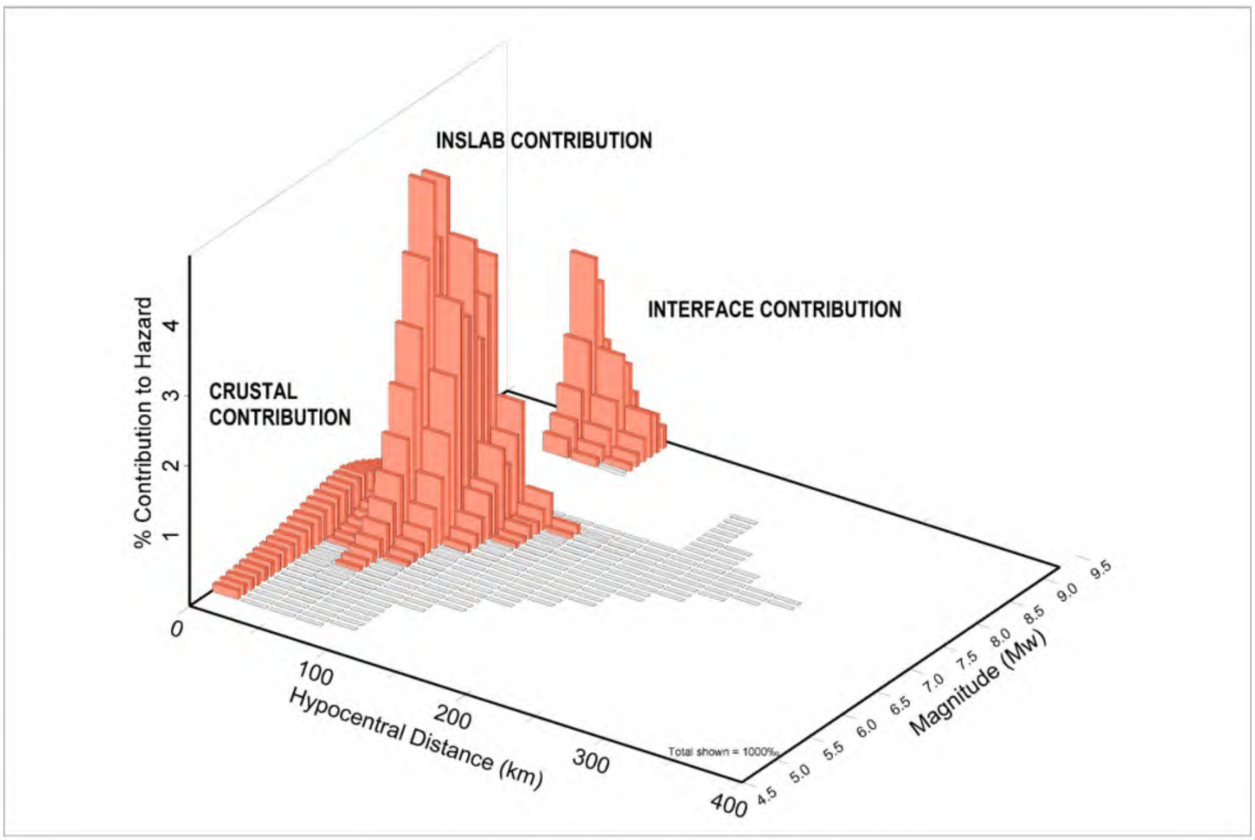


Figure E - 5: De-aggregation plot (NBC 2015 seismic hazard model) showing earthquake zone contributions to the hazard for $S_a(0.2)$ near the model slope

The Wu probabilistic method to construct displacement hazard curves (DHC) comprises the following steps:

Step A: Derivation of response spectra for 1:5,000-year Ground Motions

- Obtain the seismic hazard curves (probability versus S_a) at all available periods from the nearest GSC seismic hazard data point for crustal, inslab, and interface sources, as well as the combined seismic hazard calculations(GSC hazard spectra files GSC_SWCan_All_Sa#.txt) at a given period (e.g., 1.0 s), then plot the hazard curves for each source and extrapolate the crustal and inslab plots to at least the 5,000-year return (i.e., annual exceedance probability of 0.0001) (NRC 2021b).
- For the given period (e.g., 1.0 s) estimate a combined crustal and inslab curve to generate a non-interface curve by adding probabilities of the crustal and inslab points at a given S_a. The 1:5,000-year spectra are obtained by repeating the above procedures for each of all periods (e.g., PGA, 0.03 s, 0.05 s).

Step B: Calculation displacement

- Extrapolate the interface curve to at least the 5,000-year return by subtracting the probability of the non-interface curve from the all-sources (All_Sa# data files) curve plotted for the selected period (T_i = 1.0 s).
- The crustal and inslab (non-interface) equation is as follows:

$$P(D \geq 0) = \phi\left(-2.48 - 2.97ln(k_y) - 0.12\left(ln(k_y)\right)^2 - 0.72T_s\,ln(k_y) + 1.7T_s + 2.78\,ln(S(T))\right) \quad [8]$$

where $T_s \leq 0.7$ s (for most practical cases; see Bray and Macedo (2019) if $T_s > 0.7$ s);

$S(T) = F * S_a(1.3T_s)$; and

Φ is the standard normal cumulative distribution function.

- The interface equation is as follows:

$$P(D \geq 0) = \phi\left(-2.64 - 3.20ln(k_y) - 0.17\left(ln(k_y)\right)^2 - 0.49T_s\,ln(k_y) + 2.09T_s + 2.91ln(S(T))\right) \quad [9]$$

where $T_s \leq 0.7s$ (for most practical cases; see Bray et al. (2018) if T_s > 0.7s);

$S(T) = F * S_a(1.5T_s)$;

Φ is the standard normal cumulative distribution function; and

the overall probability for displacement from each source P(D > d) is calculated by $P(D \geq 0)$* AEP, where AEP is the annual exceedance probability (e.g., 0.0004 for a 2,475-year return)

- Calculate the displacements at a given AEP using equations 6 and 7 above for M7 earthquakes and M9 earthquakes, respectively. To generate a smooth curve, use up to 100 points of AEP (e.g., 1:475-year, 1:1,000-year, 1:2,475-year) in the calculations. Note that S_a values used in equations 6 and 7 are interpolated, if the AEP does not appear in the GSC Open File 8090.
- Construct a displacement hazard curve (DHC) using the seismic slope displacements for each of the crustal, inslab, and interface source earthquakes. Then construct the corrected total DHC from all source earthquakes by adding the curves from both sources at each displacement.

For a comparison between practice described in the previous 2010 revision of these guidelines and the currently revised probabilistic seismic slope displacement determination for a model slope, see Figure E - 6 below.

The DHC constructed for the model slope location is shown below in Figure E - 7.

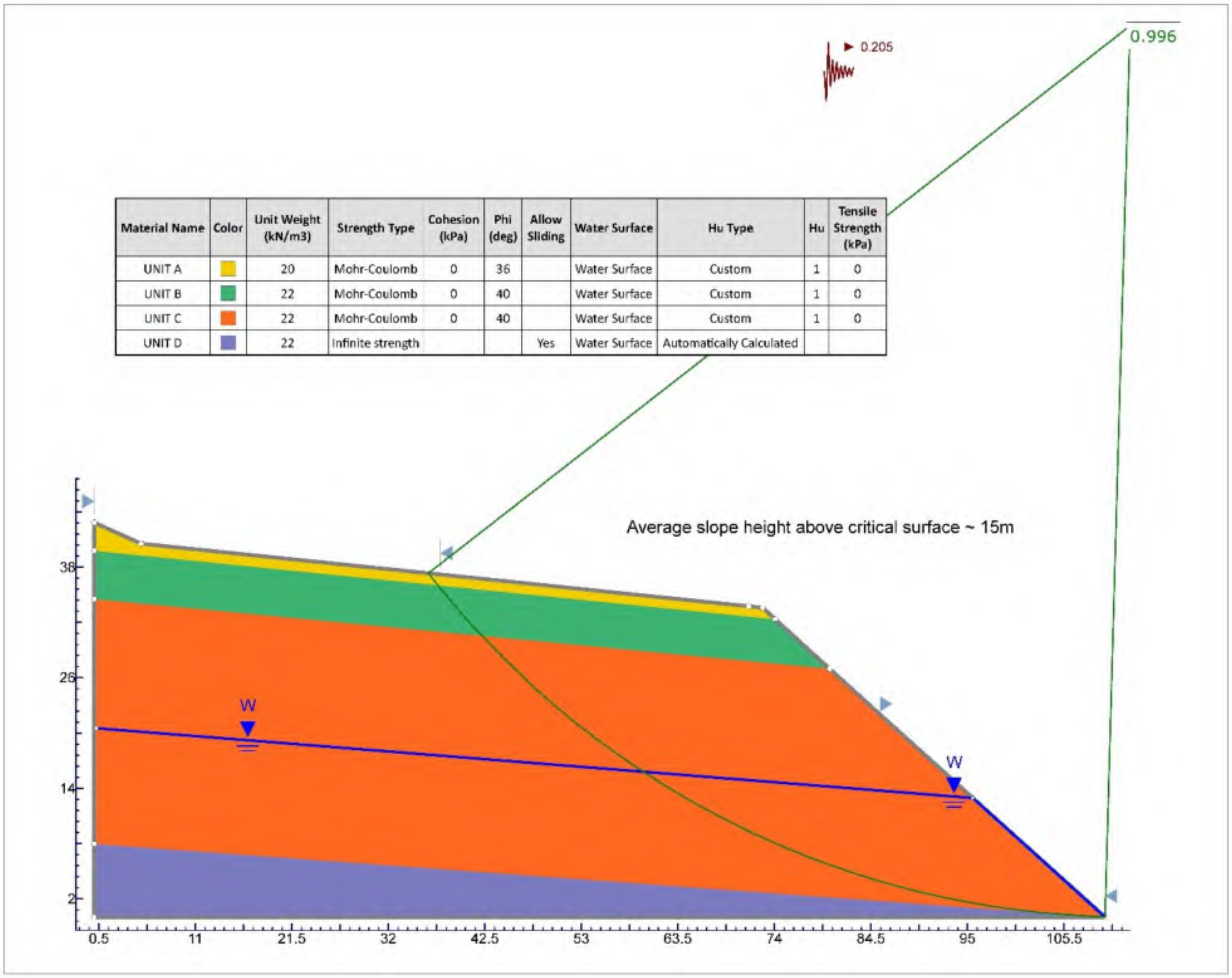

Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Allow Sliding	Water Surface	Hu Type	Hu	Tensile Strength (kPa)
UNIT A		20	Mohr-Coulomb	0	36		Water Surface	Custom	1	0
UNIT B		22	Mohr-Coulomb	0	40		Water Surface	Custom	1	0
UNIT C		22	Mohr-Coulomb	0	40		Water Surface	Custom	1	0
UNIT D		22	Infinite strength			Yes	Water Surface	Automatically Calculated		

Figure E - 6: Illustration of a model slope with k_y determination

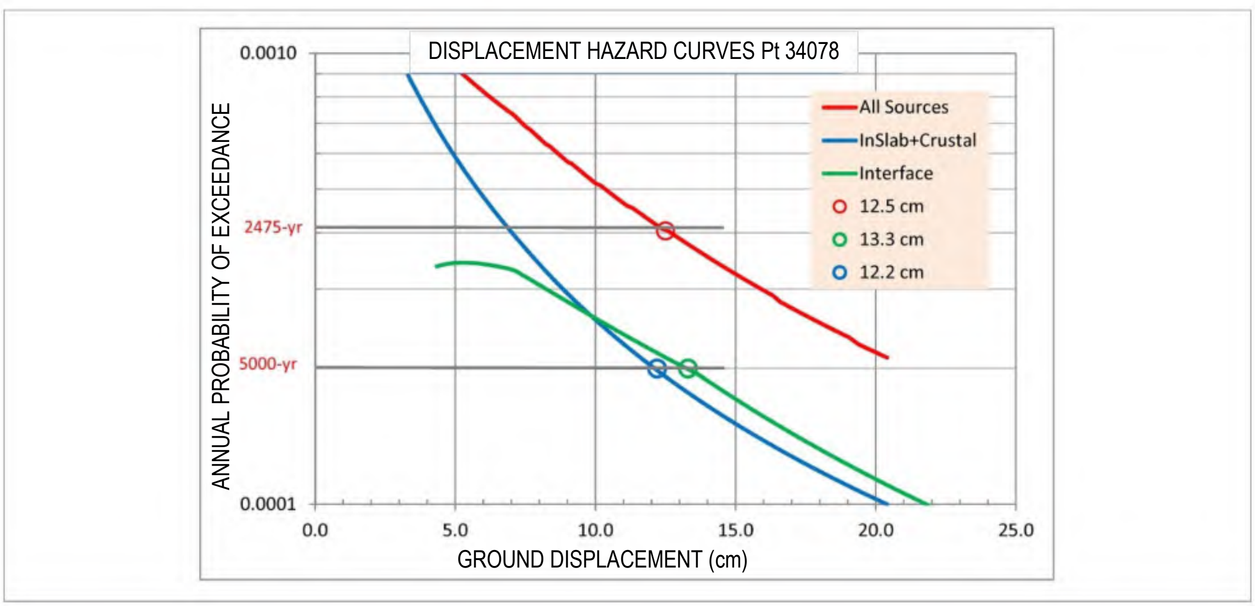


Figure E - 7: Graph of model slope displacement hazard curves for k_y = 0.21 and T_s = 0.17

Table E - 1 below indicates the shear-induced slope displacements determined using Method 1 from the 2010 revision of these guidelines and various treatments of the current analysis methods from this revision.

A review of Table E - 1 indicates that adopting the UHS – all sources seismic hazard calculations available from the *NBC 2015*, and using the BT07 procedure (developed for non-interface earthquakes) overestimates slope displacements in this case, but only marginally.

In view of the above, preliminary estimation of slope displacement along the critical surface may be carried out by seismic slope stability assessment using the *NBC 2015* and the BT07 procedure. Finalization of slope displacements should include determination of displacement hazard curves that properly consider hazard contributions from the crustal, inslab, and interface sources and under the modified Newmark methods developed for each source.

Table E - 1: Comparison of Slope Displacements (D) for a 30 m Model Slope

EARTHQUAKE ZONES [a] (GSC Pt. 34078)	V_s (m/s)	M	H (m) [b]	T_s (s)	PGA (g)	$S_a(1.5T_s)$ (g)	$S_a(1.3T_s)$ (g)	D (cm)
UHS – all sources [c]	360	7	15	0.17	0.50	0.91	–	13.9
UHS – all sources [d]	360	7	15	0.17	0.46	1.06	–	17.7
DHC – inslab + crustal construct [e]	360	7	15	0.17	0.41	–	0.96	12.5
DHC – interface construct [f]	360	9	15	0.17	0.26	0.56	–	12.5

NOTES:

Abbreviations: cm = centimetres; DHC = displacement hazard curve; g = acceleration due to gravity; GSC = Geological Survey of Canada; m = metres; PGA = peak ground acceleration; s = seconds; UHS = Uniform Hazard Spectra;

Notation: D = median displacement; H = estimated depth of sliding mass; M = moment magnitude of design earthquake; V_s = shear wave velocity; T_s = initial fundamental period of sliding mass; S_a = spectral acceleration;

[a] Crustal, inslab, and interface (subduction) zones
[b] Estimated depth of sliding mass
[c] BT07 calculation using all-sources UHC (*NBC 2005*) and Method 1 from the previous 2010 revision of these guidelines
[d] BT07 calculation using all-sources UHC (*NBC 2015*) and methods in the current revision of these guidelines
[e] BM19 calculation using inslab + crustal hazard construction (*NBC 2015*)
[f] BMT17 calculation using interface hazard construction (*NBC 2015*)

E.3.4 VOLUMETRIC-INDUCED DISPLACEMENTS (SETTLEMENT)

The magnitude of volumetric-induced displacement in non-liquefiable soils is typically substantially less than estimated slope displacements along the critical surface, and generally does not warrant practical concern. However, methods to estimate these settlements are provided below for reference.

Ground movements due to volumetric compression are not captured by Newmark-type sliding block models and should be determined by other methods. A volumetric compression model advanced by Tokimatsu and Seed (1987) for non-liquefied soils is considered to provide (in practice) reasonable estimations of soil settlement due to volumetric compression during earthquake shaking. If required, more accurate volumetric-induced displacements should be carried out using dynamic response analysis.

Estimated volumetric-induced displacement is added to the estimate of shear-induced slope displacement (determined using the Newmark-type sliding block method), to obtain total earthquake-induced ground displacement.

The simplified earthquake-induced settlement method of dry sands by Tokimatsu and Seed involves approximation of strain distribution within a soil column (1D) with estimated relative densities and utilizes a relationship of effective shear strain with depth.

E.4 LIMITATIONS

As with all analyses based on assumptions and models, the methods presented in this appendix have limitations to their applicability. In certain cases, additional judgment should be exercised when applying these methods.

The seismic slope displacement procedures are based on Ground Motion models that are subject to ongoing revisions as earthquake record databases grow and Ground Motion prediction equations evolve.

Estimation of low probability hazards 1:5,000-year or 1:10,000-year (i.e., 0.0002 or 0.0001) are based on extrapolation of the existing *NBC 2015* probability values that are less accurate than, but believed to be generally more conservative than, values that would be generated by a site-specific hazard assessment. Therefore, pseudostatic slope stability assessment extrapolation of low probability hazards should be adequate in most practical cases.

Equations 6 and 7 in subsection E.3 Slope Performance During Earthquake Shaking are valid for periods of T_s in the range $0.1 \text{ s} < T_s < 0.7 \text{ s}$, and for values of yield coefficient of k_y, in the range $0.01 < k_y < 0.5$.

This current revision of these guidelines recommends determining whether a soil slope is suitable for Residential Development using Method 1 that involves estimating the median slope displacement along a slip surface with parameters that reflect slope properties and selected a single moment magnitude earthquake (equation 1 in subsection E.2 Review of Current Practice). This slope displacement has an approximate annual probability of exceedance of 1:5,000.

It remains the opinion of the TFSSS that 15 cm or less is a tolerable slope displacement, when the sliding surface is between the building foundation perimeter and the face of the slope.

The updates to Method 1 involve combining probabilities of seismic slope displacements using hazard spectra for crustal, inslab, and interface sources to develop the displacement hazard curve for the slope.

Method 2 was based on pseudo-static limit equilibrium seismic slope stability analysis of soil slopes. This method used a slope displacement-based seismic coefficient (k_{15}) equivalent to a tolerable median slope displacement along the slip surface of 15 cm, when the slope is subjected to design

Ground Motions from a design seismic hazard characterization from all earthquake source zones and a specific slope period.

Method 2 may be considered for preliminary slope screening but is not considered suitable for finalized geotechnical designs including the establishment of geotechnical slope setback criteria for structures.

The use of k = PGA with an FS ≥ 1.0 as a basis for final judgment on slope stability is considered too conservative for use with low-probability events (for example, annual probability of exceedance of 1:2,475), and is recommended only as a preliminary screening tool.

The proposed procedure is intended to define the critical slip surface that has an estimated 15 cm of median displacement so that the building (and possibly the development) can be located behind (landward of) the critical slip surface.

The tolerable slope displacement of 15 cm is proposed as a guide, based on experience with residential wood-frame Construction, and has been generally adopted in the industry. These guidelines are not intended to preclude QPs from selecting another value that they deem appropriate.

This appendix only addresses the mechanics of the proposed new methods for analyzing seismic slope stability of soil slopes. Other aspects of the analyses such as the development of rational geological models and selecting appropriate shear strength parameters should reflect best current practices.

E.4.1 SEISMIC RETROFIT AND LIQUEFACTION ASSESSMENT GUIDANCE

The following summary of current guidance is reflected in the *SRG-3* (Engineers and Geoscientists BC 2022) and the *Liquefaction Guidelines for Inland Richmond Schools* (Engineers and Geoscientists BC 2020).

The third edition of the *Seismic Retrofit Guidelines SRG-3* utilizes a performance-based philosophy which complements the building code for new Construction by providing a rational method for life-safe and cost-effective retrofit of existing buildings. The key philosophy in this approach is to achieve life safety by reducing the probability of structural collapse to acceptable levels instead of concentrating on damage prevention.

The changes in seismic hazard maps produced by the Geological Survey of Canada (GSC) from 2010 to 2015 have been quite substantial as a result of advancements in the state of knowledge about seismic hazards in Western British Columbia. The significant increase in perception of seismic hazard necessitated a complete re-evaluation of [the] approach from the *SRG-2* to the *SRG-3*, in order to reduce unnecessary conservatism and produce a methodology that, while incorporating the latest understanding of seismic hazard, provides results which are economical and feasible. Three earthquake source mechanisms are now considered in the analyses: (a) crustal, (b) subcrustal, and (c) subduction.

The *SRG-3* includes Module 11 that contains detailed liquefaction assessment and mitigation procedures to make it possible to utilize the guidelines effectively on poor and liquefiable site soil conditions prone to lateral soil spreading and differential vertical settlement effects, including;

- site investigation key work scope elements;
- evaluation of liquefaction potential;
- Consequences of liquefaction in terms of ground displacements and settlements;
- liquefaction under M=9.0 earthquakes; and
- mitigation of liquefaction effects by structural retrofits and geotechnical measures.

The *SRG-3*, Module 11 did not include guidance on lateral displacements at potentially liquefiable sites using the Bray (2007) method (for sites with non-liquefiable crust >3 m thick).

E.5 LIQUEFACTION DISPLACEMENT ASSESSMENTS

E.5.1 BACKGROUND

In 2007, the Greater Vancouver Liquefaction Task Force published their geotechnical design guidelines for buildings on liquefiable sites to establish best practices based on the opinions and recommendations provided by technical expert members of the Task Force. The report provided revised general guidelines from the original 1991 liquefaction guidelines to reflect advances in knowledge and technology.

Recent revisions and recommendations to those guidelines were published in 2017 in the *Seismic Retrofit Guidelines,* Third Edition (*SRG-3*) (Engineers and Geoscientists BC 2022), and in 2020 a memorandum from the Technical Review Board titled *Liquefaction Guidelines for Inland Richmond Schools* (Engineers and Geoscientists BC 2020).

E.5.2 LEVELS OF EFFORT FOR SEISMIC SOIL STABILITY ANALYSES

Levels of effort for seismic soil stability analysis can be found in Appendix B: Landslide Assessment – Determining the Level of Effort, subsection B.2.4 Level of Effort Tables B-1 to B-6.

E.6 REFERENCES – APPENDIX E

E.6.1 REFERENCES

The following documents are referenced in Appendix E of these guidelines:

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E.6.2 RELATED DOCUMENTS

The following resources related to this appendix are provided for information:

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APPENDIX F: EVOLVING PRACTICE

F.1 INTRODUCTION

Processes for Landslide Assessments are continually evolving and improving as more analytical methods are discovered and existing methods are refined.

This appendix lists the following specialties that are still evolving, and provides details for the Qualified Professional (QP) to consider when undertaking Landslide Hazard or Landslide Risk assessments that may involve these types of activities.

- Quantitative risk assessments (subsection F.2)
- Digital deliverables (subsection F.3)
- Geospatial databases and web-based platforms (subsection F.4)
- Landslides and climate change (subsection F.5)
- Hazard chains (subsection F.6)
- Post-fire assessments (subsection F.7)
- Landslide Hazard mapping (section F.8)

F.2 QUANTITATIVE RISK ASSESSMENTS

In Canada, Landslide quantitative risk assessments (QRAs) are gaining popularity amongst decision-makers and consultants. The majority of Landslide QRAs are carried out in British Columbia (BC), followed by Alberta. Landslide Risk assessment is also carried out in parts of Quebec for high-level planning purposes.

As discussed in Section 3.2.4 Quantitative Risk Assessments, these guidelines and others, such as the following federal and provincial guidelines, encourage the use of QRAs in Landslide Risk management:

- *Landslide Risk Case Studies in Forest Development Planning and Operations*, BC Ministry of Forests, Land Management Handbook 56 (Wise et al. 2004)
- *Canadian Technical Guidelines and Best Practices Related to Landslides: A National Initiative for Loss Reduction*, published by Natural Resources Canada (Porter and Morgenstern 2013)
- *Land Procedure – Landslide Risk Management*, published by the BC Ministry of Forests, Lands, Natural Resources, and Rural Development (BC MFLNRORD 2014)
- *Draft Guidelines for Steep Creek Risk Assessments in Alberta*, published by Alberta Environment and Parks (Alberta Environment and Parks 2017)

In conducting QRAs for loss of life, both individual risk (also known as the probability of loss of life of individuals, or PDI) and group risk (also known as societal risk) are typically assessed.

Individual risk typically focuses on the person judged to be most at risk, corresponding to those who spend the greatest proportion of time in the Landslide zone; for example, a young child, a stay-at-home person, or an elderly person. Individual risk is calculated using the following equation:

$$PDI_j = \sum_{i=1}^{n} P(H)_i P(S|H)_{i,j} P(T|S)_{i,j} V_{i,j}, \qquad [10]$$

where PDI_j is the PDI at a given building (j);
$P(H)_i$ is the annual probability of a geohazard scenario[14] (i);
$P(S|H)_{i,j}$ is the spatial probability of impact of geohazard scenario (i) at a given parcel (j);
$P(T|S)_{i,j}$ is the temporal probability of a person occupying a building at parcel (j);

[14] Note that the probability of a geohazard scenario is the product of event probability, avulsion probability (where applicable), and flow mobility probability.

$V_{i,j}$ is the probability of fatality (vulnerability) given impact by the estimated hazard intensity[15]; and

n is the number of geohazard scenarios.

Group risk evaluates the number of people who could be killed by a Landslide-related hazard, considering all people located within the consultation zone. Group risk is derived from a calculation of fN pairs, where the annual probability of a given geohazard scenario, f_i, corresponds with an estimated number of fatalities, N_i, defined with following equations:

$$f_i = P(H)_i, \text{ and}$$
$$N_i = \sum_{j=1}^{n} P(S|H)_{i,j} P(T|S)_{i,j} V_{i,j} E_j, \qquad [11]$$

where $P(H)_i$, $P(S|H)_{i,j}$, $P(T|S)_{i,j}$, and $V_{i,j}$ are the same as defined in equation 10 above;

n is the total number of individual parcels; and

E_j is the number of people exposed to the hazard in parcel (j).

The schematic diagram in Figure F - 1 explains the various terms. The diagram shows two scenarios for the same site, with the total quantified risk at each building from both scenarios shown in the bottom of the call-out bubbles.

It is the responsibility of the QP to know how to conduct a QRA and be able to justify the assumptions and methods used in the QRA.

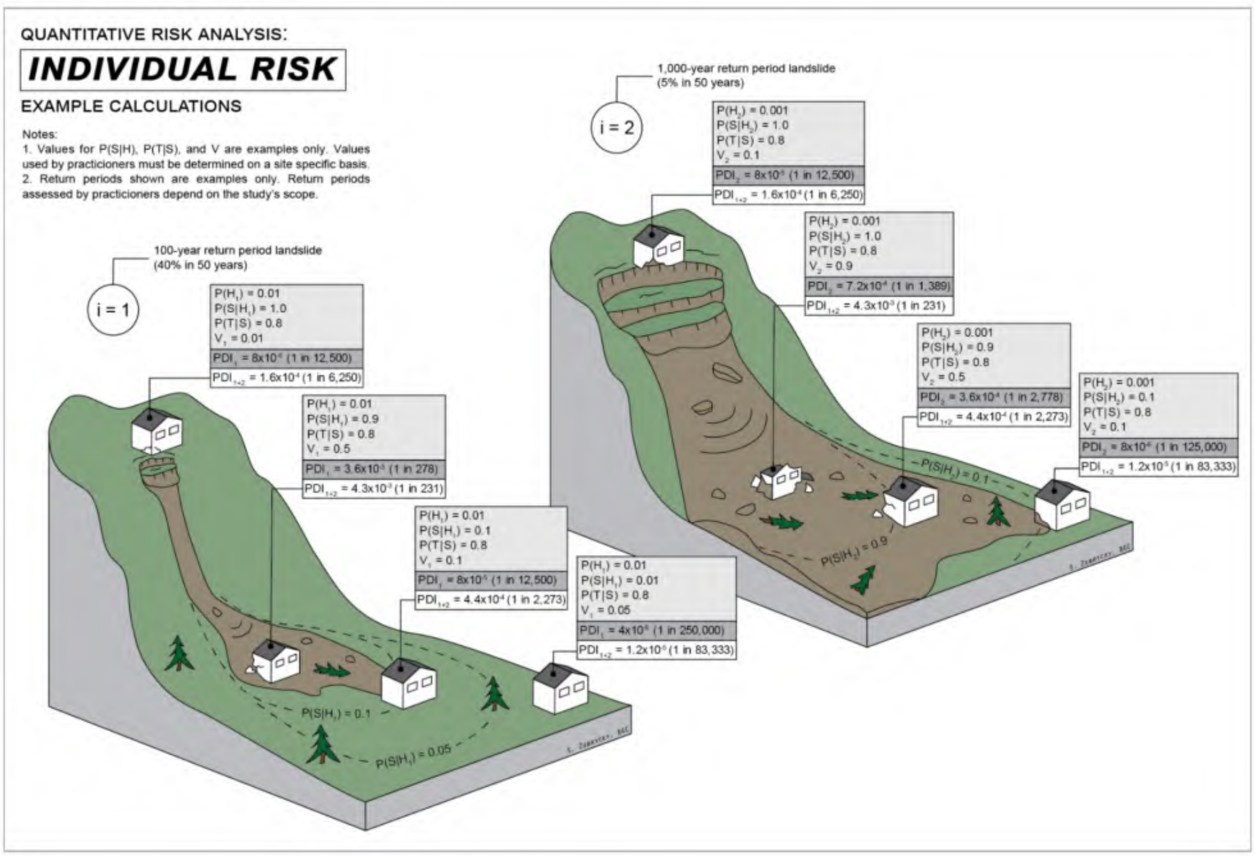


Figure F - 1: Diagram illustrating the terms of the PDI risk equation

NOTES:
Abbreviations: PDI = probability of loss of life of individuals
Artwork credit: S. Zubrycky, BGC

[15] Intensity refers to the destructive potential of a Landslide at the parcel level.

F.2.1 RISK EVALUATION FRAMEWORK

Risk evaluation is the final required step of a Landslide Risk assessment. It compares the estimated Landslide safety risks with available resources and with perceptions of tolerable risks, to decide what actions, if any, are needed.

Given the Landslide Risk at a specific location, the risk evaluation is intended to determine if "the land may be used safely for the use intended" and if "development may safely occur." Although these statements are used in provincial legislation, the term "safe" is not defined by the legislation (see Appendix A: Legislative Framework).

F.2.1.1 Determining Levels of Landslide Safety

Three methods are used in BC to define Levels of Landslide Safety, which can be used independently or in combination: encounter probability, individual risk, and group or societal risk.

1. **Encounter probability**: Also known as "partial risk," encounter probability is the combination of hazard probability and the probability of the Landslide reaching the Element at Risk (i.e., $[P(H)_i\ P(S|H)_{i,j}]$). It focuses on the probability that an Element at Risk is impacted by a Landslide, without considering economic damages caused by Landslide impact or the probability of fatality, given impact.

   In reducing tolerable risk to an encounter probability, it assumes the highest Consequence (e.g., $P(T|S)_{i,j}$), and in that regard would be conservative.

   Cave (1993) provides an encounter probability framework that has been commonly applied in BC and is still being used to govern development permit applications at the Fraser Valley Regional District.

2. **Individual risk**: Individual risk is defined as the incremental probability of death due to a Landslide for a specific individual.

   – The District of North Vancouver has adopted individual risk criteria, with public consultation (Tappenden 2014), and similar standards have been adopted by the District of Squamish. For those jurisdictions, annualized individual life-loss risk from Landslides must be less than 1 in 10,000 at existing development, and less than 1 in 100,000 at new development.
   – Several studies have found it is unreasonable to achieve the 1:100,000 threshold where risk avoidance is not an option (e.g., redevelopment of an existing building), and have advocated for the 1:10,000 threshold plus a requirement to manage risk through a combination of education of the population at risk, monitoring, warning systems, emergency planning, and reasonable investments in structural protection measures following the ALARP (as low as reasonably practicable) principle.
   – The Cowichan Valley Regional District has recently adopted this revised approach, whereby, for new or existing development, the annualized individual life-loss risk from Landslides must be less than 1 in 10,000 with ALARP. In its draft (and as yet unadopted) guidelines, the Village of Lions Bay refers to 1 in 10,000 risk threshold for building permit on an existing lot, or subdivision of up to four lots (including the existing lot), and 1 in 100,000 for five lots or more (including the existing lot).

   Individual risk is generally applied for smaller projects, and where the risk at the site is of relevance to the proponent and/or approving body.

3. **Group or societal risk**: Assessment of group or societal risk is conducted when the broader Consequences of the Landslide Hazard need to be considered, including the potential total number of people killed, economic losses, environmental losses, and service disruptions.

   Compared to assessment of individual risk, assessment of group risk may be far more challenging, labour intensive, and costly, as the risk affecting the entire consultation zone must be estimated. Therefore, for lower level of effort classes group risk assessment is rarely conducted, but is required for higher-Consequence proposals with Class 2 to 3 level of effort.

In BC, societal risk has generally referred more narrowly to group risk, and is the relationship between the probability of, and number of, people killed in a Landslide. Societal risk can be expressed in three ways:

a) **fN diagram** (Figure F - 2), which displays the estimated number of fatalities (N) for each Landslide scenario, with occurrence probability (f) as a series of points on the diagram. The points can be compared to a risk tolerance threshold or reference line to identify scenarios with intolerable risk. It also identifies which scenarios contribute most to total risk, which scenarios should be the focus of risk management actions, and how much risk reduction is achieved by the proposed mitigation measures.

b) **Probable life loss (PLL)**, which is the product of occurrence probability (f) and number of fatalities (N). PLL describes the expected number of deaths over a period of time. The PLL from a single risk scenario (i.e., a single fN pair) can be compared against other scenarios, or PLL from various independent risk scenarios can be summed to yield the total PLL for an assessed Landslide or study area. If probability is presented as an annual probability, then it is the annual probable life loss (APLL). PLL is a valuable tool for cost-benefit analysis and comparison of mitigation options (e.g., risk before and after mitigation), because it presents all combined risk scenarios as a single value.

c) **FN diagram** (Figure F - 3), which displays the probability of N or more fatalities. Risk scenarios are combined to form a single curve that can be compared to a reference line. Where the risk curve plots above the reference line, there is an increasing need to reduce risk through structural or other measures. Where the risk curve plots below the line, there is a decreasing justification for risk reduction. The District of Squamish has adopted a societal risk tolerance objective for a specific project that is equivalent to the reference line in Figure F - 3.

F.2.1.2 Determining Risk-Reduction Measures

Another important factor that should inform risk-evaluation decisions, particularly with an existing development, is the practicality and cost-effectiveness of risk-reduction measures. Given that funding for risk-reduction measures is limited in BC, QPs should initially seek to maximize any risk-reduction measures that can be achieved with available resources, and then seek to meet risk-tolerance thresholds. This approach is still in line with the ALARP principle.

Figure F - 3 uses the original Hong Kong GEO (1998) criteria to assess risk, with some changes for application in BC. This method stipulates that, for a new development, risk must be reduced to below the blue dashed reference line. For existing development, the ALARP principle applies to both below and above the reference line. Figure F - 3 also shows that the further risk plots towards the upper-right corner of the graph, the more beneficial risk-reduction measures become. For risks plotting towards the bottom-left corner of the graph, there is little justification in providing mitigation. The classes refer to the level of effort categories shown in Appendix B: Landslide Assessment – Determining the Level of Effort.

The decision on the types of measures required to fulfill the ALARP principle will vary from case to case, and the QP should develop them in collaboration with the Local Government and the population residing within the consultation zone.

Figure F - 4 shows hypothetical examples of group risk profiles and their respective interpretations.

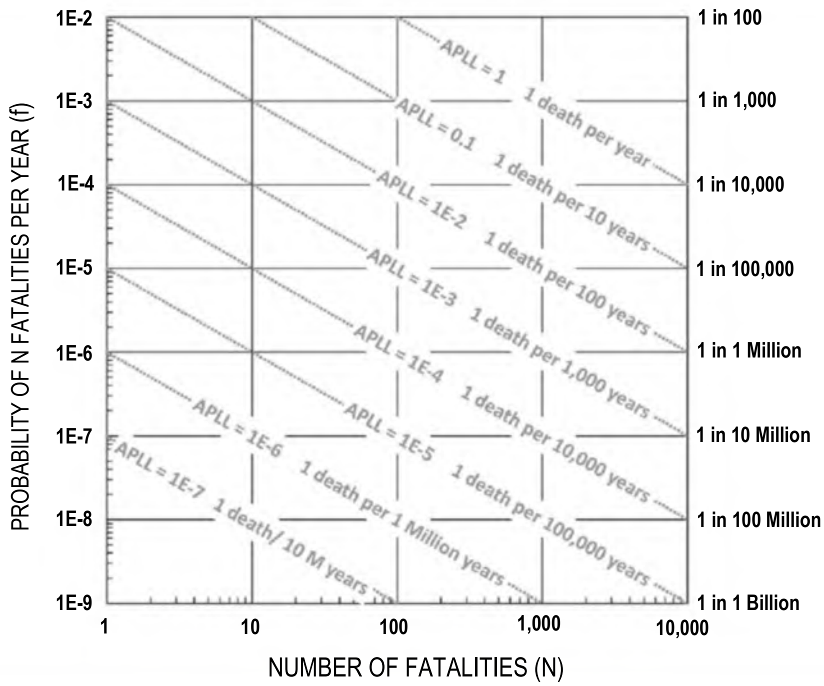


Figure F - 2: An fN diagram, showing annual probable life loss (APLL) contours; APLL = 1E-3 is a commonly applied risk tolerance threshold

NOTES: Source: Strouth and McDougall 2021.

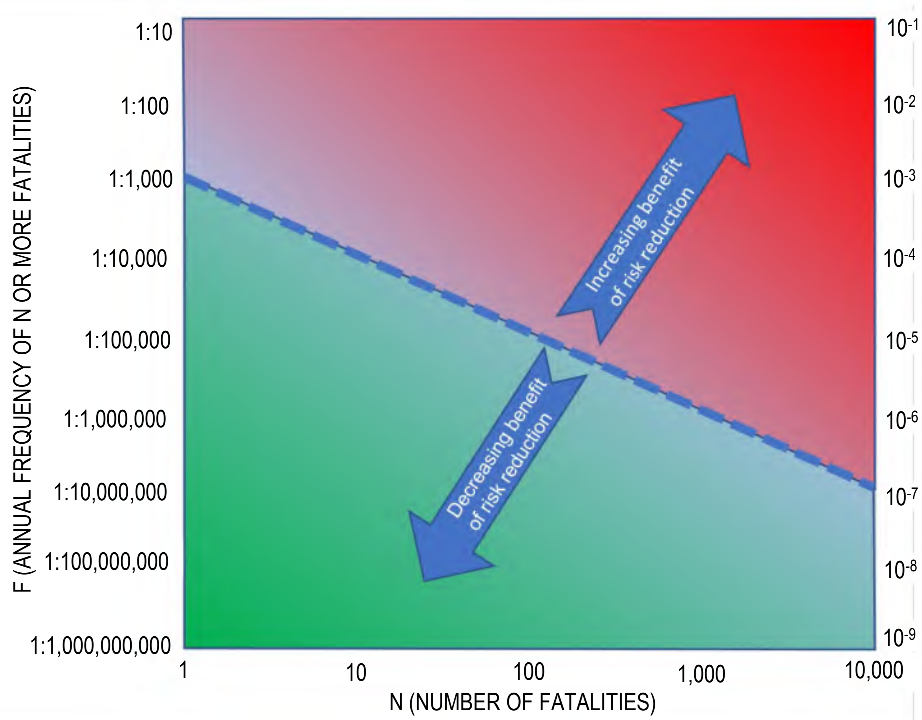


Figure F - 3: Illustration of an FN diagram for societal risk tolerance

NOTES: Source: Based on Hong Kong GEO (1998), annotated and coloured for these guidelines. Note that the number of fatalities is not equivalent to the number of people at risk (see upper horizontal axis) within the consultation zone, which depends on mortality given the specific geohazard. Classes refer to the level of effort as per Appendix B.

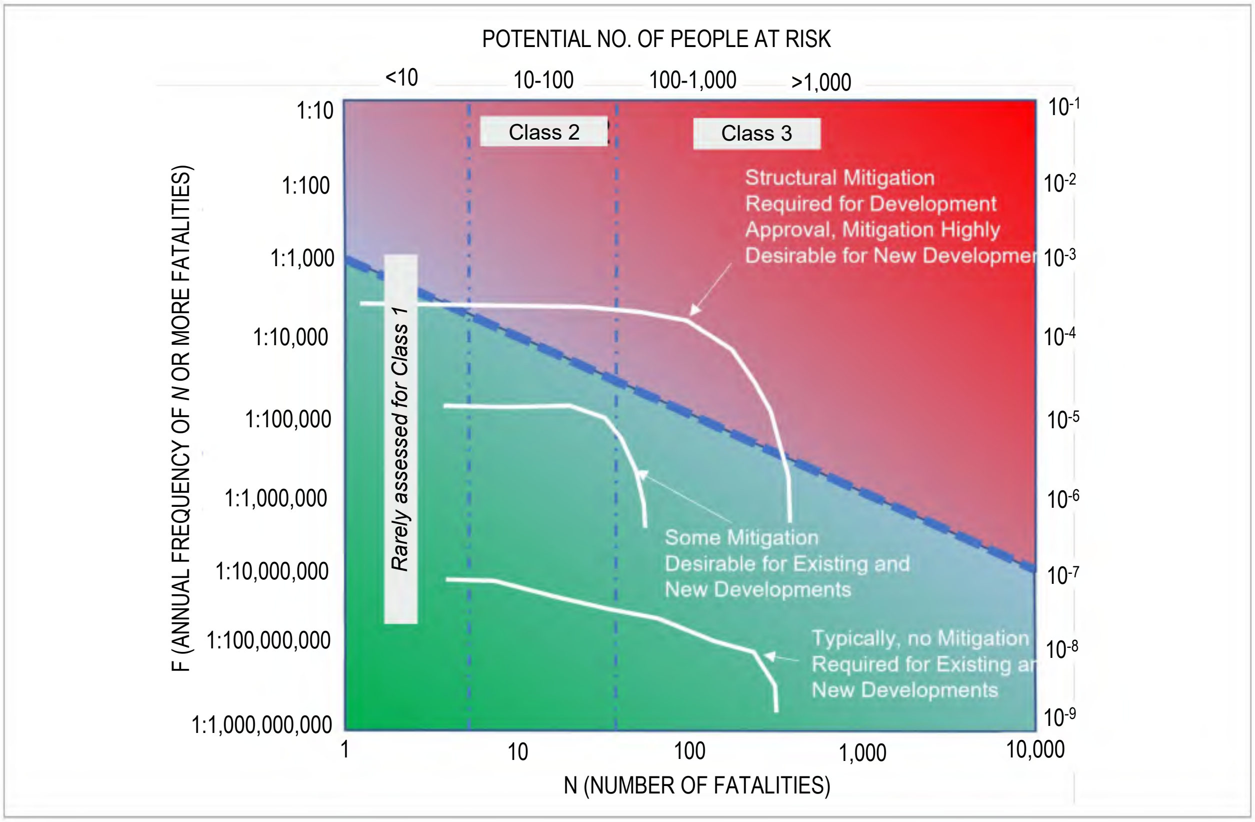


Figure F - 4: Illustration of hypothetical group risk profiles and interpretations

NOTES: The actual response of the Client will depend on several other considerations such as distribution of PDI risk, available budget, permitting constraints, land ownership, technical feasibility, ecological constraints, and aesthetics.

F.2.2 RISK-BASED SITE PRIORITIZATION

Risk-based site prioritization studies are being completed more frequently in BC, particularly those pertaining to steep creek hazards. The QP needs to be aware of such studies to contextualize the individual site assessments within that framework, where applicable.

Landslide Assessment usually starts with the systematic identification and prioritization of multiple geohazard areas at regional scale. The purpose of risk prioritization is to gain an understanding of relative risk across multiple sites, in order to:

- develop and implement policies and bylaws (e.g., Official Community Plans), including defining areas with regulatory requirements for Landslide Assessment;
- undertake planning related to land use, and geohazard and emergency management, including the selection of areas of interest for Landslide Assessment; and
- prepare or evaluate funding applications for Landslide Assessment.

Risk-based site prioritization is completed in advance of site-specific assessment and should consider information readily available at a consistent level of detail across the region of interest. QPs should consider a combination of hazard, exposure, and vulnerability when determining a priority rating for a given site, and address questions such as the following:

- **Hazard**: What is the relative chance that geohazards will occur and impact areas containing Elements at Risk?
- **Exposure**: What types and relative values of Elements at Risk are exposed to hazard?
- **Vulnerability**: Given impact, what is the relative potential for damage or loss?

As a relative measure of risk, risk prioritization supports but does not replace Landslide Risk assessment.

F.2.3 RISK CREEP

For many situations, individual risk may be assessed as very low, but societal or group risk in the same situations may not be. As such, it is important for individual risk and societal risk to be considered together (Evans et al. 1997).

Furthermore, the QP should be aware that societal risk is not a constant, and risk creep may occur over time. For example, imagine an area subject to debris flows or rockfall and rockslides in which a small subdivision is proposed. Upon study, the group risk is considered tolerable, due to the low density of proposed homes in the area and the relatively low hazard. However, over time, many more homes may be built in the area, or existing ones replaced by higher density developments (as can be observed in large parts of BC). Or consider the case, holding the hazard constant through time, but adding density, then individual risk (assessed at the site) will remain constant and within acceptable bounds, while societal or group risk (assessed over the entire consultation zone) will increase and may become unacceptable.

The potential for these scenarios should be highlighted by the QP, who should encourage the Local Government to regularly update the group risk estimates and be informed about the potential for such risk creep.

The QP and the Approving Authority may find it useful to establish a development density threshold or employ zoning or Covenants to manage density, because risk-based mitigation recommendations can then be placed in legal documents and remain in effect until a future formal review is initiated.

These guidelines do not stipulate using a hard threshold, but a risk-informed decision-making process in which, should the tolerance thresholds be exceeded, additional mitigation measures proportional to the risk increase can be contemplated and planned for. In some cases, particularly when the hazard is not structurally mitigatable (i.e., rock avalanches), imposing a limit to development densification may be warranted and could be enshrined in bylaws or building Covenants.

Optimally, the above considerations should be developed as part of community planning processes, rather than arising from individual development approvals. Approving Authorities may question recommendations made in site-specific reports, especially where such recommendations suggest that the Approving Authority assume long-term risk monitoring. Rather, the Approving Authority may take the position that the development approval cannot depend on the Authority bearing the responsibility for risk monitoring over time. Such refusal would then likely result in limits to development densification, especially where the increase in risk cannot be reasonably compensated, even with an increase in mitigation efforts.

F.3 DIGITAL DELIVERABLES

The deliverables of some Landslide Assessments may include digital forms of data (e.g., GIS, CAD, and database files), and may utilize web-based forms of data transmission (e.g., web applications, data services). As such, the QP should be aware of certain considerations, such as the following:

- Deliverables may be updated regularly or even continuously in both time and space, such as with instrumentation and monitoring data, or via periodic site inspections delivered via web forms.
- Versions need to be identified so Clients know they are relying on the latest version available.
- Digital products may be combined in numerous ways through data interactions between the Client, the QP, and other third parties, and use software that integrates the steps of desktop and field data collection, analyses, and user interaction into the results.
- Web maps may combine deliverables with third-party data sources (e.g., base map features) and allow for multiparty interaction among users (e.g., uploads, downloads, and data streaming).

The provision and management of digital deliverables raises complex issues related to professional responsibility, liability, and the maintenance of record copies. Comprehensive treatment of these issues is outside the scope of these guidelines.

At minimum, when providing digital information related to Landslide analysis for existing and/or proposed infrastructure development, the QP should:

- provide limitations and uncertainties specific to the use of digital deliverables, and include appropriate metadata with any data products;
- understand the end user's case(s) for the provision of dynamic digital information, and ensure that the limitations, uncertainties, and reliability of the dynamic information provided, and the system providing it, is appropriate to that user's case(s);
- include report disclaimers limiting the use of deliverables by third parties that are specific to the data provided, such as limitations related to geographic scale of use, reliance on third-party data sources, and user interface design; and
- define and track data versions of the deliverables (maps or other types of data) when providing regular updates, and maintain record copies that will take precedence over any other copy or reproduction.

F.4 GEOSPATIAL DATABASES AND WEB-BASED PLATFORMS

Today, Landslide Hazard assessments typically involve the use of information technologies and platforms. The QP may wish to bring these advances to the attention of Local Governments and provincial governments, to facilitate future assessments and coordinate and manage geohazard data from various stakeholders.

- **Electronic Geographic Information Systems (GIS)** have been used for over fifty years to aid in the management and analysis of spatial and geographic data, including data and imagery related to Landslide Hazards. The general availability of web-based user interfaces to GIS over the past ten years has allowed GIS data and information to be shared more broadly, with the only end-user requirement being a web browser.
- **Data management methodology** is a key consideration when implementing GIS systems for Landslide Hazard assessments. Local Governments and provincial governments need to consider the full lifecycle of data management, from digital field data collection through to data storage and to consumption by analysts and end users.
  - Local Governments sometimes provide a simple threshold (for example, a 25% slope) to trigger geotechnical slope assessments. While this is perhaps a useful starting point, thresholds tend to oversimplify the potential issues, as slope failures can occur at much lower angles, or at these and higher angles, the slope may be stable. The advent of large data management systems allows a more multivariate approach to defining which slopes deserve geotechnical assessments and Landslide Assessments.
  - The QP should understand that the capacity and capability of Local Governments to generate such maps varies substantially across the province, which implies a large variety of the depth and breadth of information available as a steppingstone for the QP's assessment.
  - Irrespective, appropriate hazard assessments are not dependent on high-quality geospatial or other data. The QP will need to work within the limits set by the available data, whether it is digital or available as paper maps.
- **Remote sensing**: Data obtained manually or through remote sensing are often more valuable when paired with local and regional weather and other earth observation data. Satellite remote sensing missions, such as Sentinel-1 C-band radar, offer operational global coverage at high temporal frequency and relatively high resolution.

F.5 LANDSLIDES AND CLIMATE CHANGE

F.5.1 EFFECTS OF A CHANGING CLIMATE ON LANDSLIDES

Humans have entered an era in which our climate is more akin to the Eemian or the Pliocene than any period of the Holocene. This realization is profound because Landslide scientists base much of their deductions, extrapolations, and inferences on using the past as a key to the future. As noted by Milly et al. (2008), however, “stationarity is dead.” Despite this widespread recognition that the past no longer accurately represents the future, much confusion prevails in the media and elsewhere as to teleconnections between a changing climate and spatial and temporal Landslide frequency, magnitude, and intensity.

Claims that a changing climate will lead to more Landslides, higher magnitudes, and increased intensities are oversimplifications. While true in some regions and for some Landslide types, the opposite may be true in other regions or for different Landslide types. The difference, while reflecting many variables, can be discussed in terms of the major factor determining slope stability: changes in the moisture regime. Of course, rising sea levels may also lead to increased erosion of coastal bluffs.

It has long been known that atmospheric temperature and water content are connected (Clausius 1850). The well-known Clausius-Clapeyron relationship (Çengel and Boles 1998) states that with a one-degree Kelvin warming, an increase of 7% moisture content can be expected. However, this process does not apply uniformly across the globe. Especially in the tropics, latent heat release by precipitation may lead to the so-called Super Clausius-Clapeyron (SCC) events with moisture increases as much as double those expected from the CC relationship (Lenderink et al. 2017). For example, Prein et al. (2017) found that for all regions of the contiguous United States (and southern Canada), extreme precipitation (defined by the 99.95th percentile) is expected to increase at a rate of approximately 7% per degree Celsius, but that this scaling relationship is strongly dependent on region, temperature, and moisture availability. Complexity in the scaling relationships has also been discussed by Zhang et al. (2017). Dynamic or thermodynamic components may prevail in any given storm or extreme event scenario, and attribution to climate change is still fraught with substantial uncertainty.

F.5.2 CONSIDERING CLIMATE CHANGE WHEN ASSESSING SLOPE STABILITY

QPs should consider the possible effects of a changing climate when assessing the probability of occurrence of a natural hazard. Slope stability is affected by both temperature and precipitation, and current probability of Landslide occurrence is based on historical environmental observations. Thus, current probabilities may not accurately represent the probability of occurrence under a different (future) climate state, and utilizing current probability information may be inappropriate to evaluating actual risk. Depending on the magnitude and trend of the change, the difference in probability of occurrence could be statistically significant (e.g., a 1 in 500-year event becomes a 1 in 50-year event 20 years from the present).

Precipitation and air temperature estimates for future periods (usually to 2100 AD) are available from the Canadian Centre for Climate Modelling and Analysis (CCCMA) (Government of Canada 2017). But while data from the CCCMA may be considered, best results may be derived from ensemble climate model data of the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP; in which the CCCMA is a participant), which informs the climate change assessment reports of the Intergovernmental Panel on Climate Change (IPCC). CMIP is currently in its sixth round (CMIP6), and the output from the approximately 100 global climate and earth system models is available via a data portal hosted by the United States Department of Energy, Lawrence Livermore National Laboratory (US DOE 2022). Output from CMIP5, a more mature suite of global climate models is also available from this database, as well as from the Pacific Climate Impacts Consortium (PCIC 2022).

It should be noted that climate model output data may be difficult to correctly extract and interpret. Thus, QPs are advised to engage a professional climatologist before acquiring and using climate model output data, regardless of data source.

Using climate projections obtained from downscaled general circulation models (GCMs) for evaluating future stability conditions of individual slopes, or of Landslides at specific sites or regionally, relies on a modelling framework consisting of a climate component and a slope stability component. For example, in Figure F - 5, the climate component (A) provides models outputs from downscaled GCMs suited for Landslide modelling (B). The advantage of using downscaled GCM outputs for slope stability modelling is the ability to integrate synthetic climate records of rainfall (and temperature) into existing and consolidated slope stability engineering, geomorphological, and hydrological modelling frameworks, and their associated software tools.

Where synthetic rainfall and temperature records are available for the past (for calibration) and the future (for projections), effects of the climate variables can be evaluated for the target slopes, and scenarios can be constructed that provide information on the expected/projected trend of the stability conditions. For single slopes or Landslides, the future average rate of movement and the total displacement in a period can be predicted (Comegna et al. 2013; Rianna et al. 2014), allowing for an estimate of whether a Landslide is expected to accelerate or decelerate, depending on the considered climate scenarios.

In the case of multiple slopes or Landslides in a catchment or landscape, a regional approach is required, and the downscaled climate variables are used as input to physically-based distributed models (Chang and Chiang 2011), spatially distributed hydrological models (Ciabatta et al. 2016), or empirical threshold-based models (Jakob and Lambert 2009; Jakob and Owen 2021), to evaluate the expected increase or decrease in the proportion of unstable areas, or in the probability of exceeding Landslide occurrence thresholds (Gariano and Guzzetti 2016).

F.5.3 LANDSLIDE RESPONSE TO CLIMATE CHANGE

These guidelines are not intended to provide technical or systematic instructions for how to carry out these activities but contain general guidance for moving towards more detailed analyses.

The information in Table F - 1 is provided as a tool for understanding basic underlying climate change trends and the likely responses of Landslides to the various forcing mechanisms. It is the QP's responsibility to research and/or quantify the effects of climate change on the specific Landslide type that is being investigated.

It is also the QP's responsibility to decide, in collaboration with the Client and Approving Authority, the degree of detail that is appropriate for the study in question. In general, the principals in Appendix B: Landslide Assessments – Determining the Level of Effort apply. The higher the level of the study, the higher the effort that ought to be expended on including the effects of climate change for the existing or proposed development.

The QP should also review the *Professional Practice Guidelines – Developing Climate Change-Resilient Designs for Highway Infrastructure in British Columbia* (Engineers and Geoscientists BC 2020), as that guidance may pertain to the development in question and include principles that may apply to both types of study.

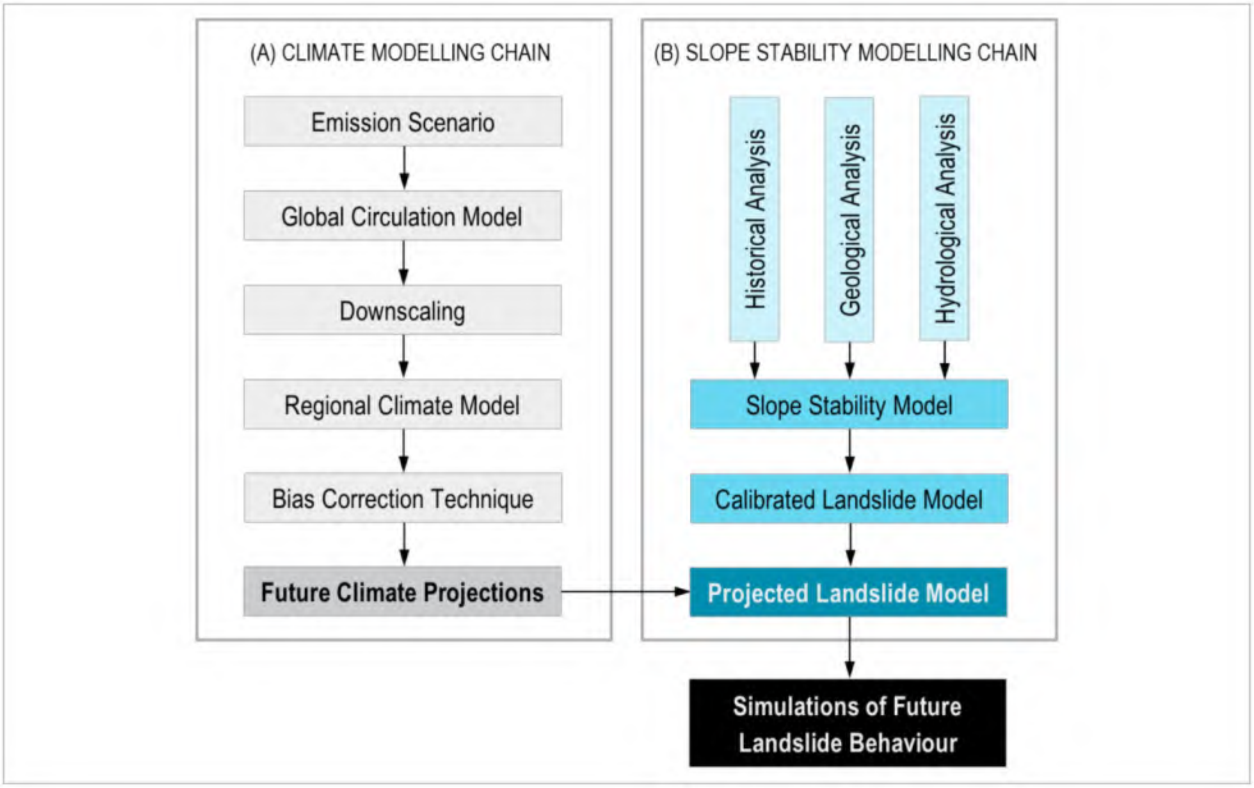


Figure F - 5: Schematic of a Landslide-climate modelling logical framework, with (A) the climate modelling chain, and (B) the slope stability modelling chain

NOTES: Figure F-5(A) is adapted from Rianna et al. (2014).

Table F - 1: Simplified Summary Chart of Landslide Response to Climate Change with Overall Predictive Uncertainty

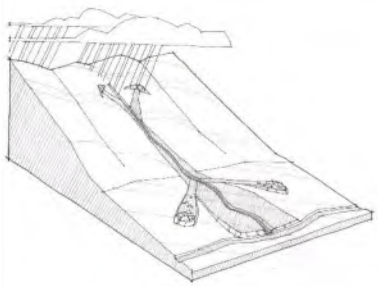
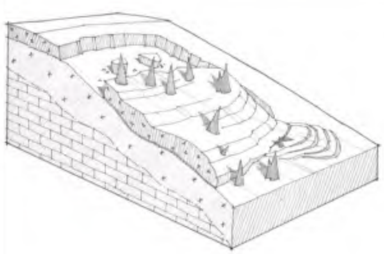
LANDSLIDE TYPE	GENERAL CHANGES IN TEMPERATURE AND PRECIPITATION			INCREASE IN RAINFALL INTENSITY (F-M)	CHANGES IN FREEZE-THAW CYCLES	OVERALL PREDICTIVE UNCERTAINTY[a]
	WARMER	DRIER	WETTER			
DEBRIS FLOWS AND DEBRIS AVALANCHES	**DIRECT EFFECTS**					
	• More events (in permafrost-underlain terrain) • Possibly larger magnitude (in permafrost-underlain terrain) • Changing temporal and spatial patterns of snowfall vs. rainfall	• Fewer events • Smaller magnitude	• Possibly more events • Possibly larger in supply-unlimited basins, or smaller if supply-limited	• More events (regionally) if accompanied by sufficient antecedent moisture • Magnitude dependent on basin type	• Possibly higher weathering and debris supply in upper watershed • Magnitude changes dependent on rainfall pattern changes	MODERATE
	INDIRECT EFFECTS					
	• Higher susceptibility to wildfires and post-fire debris flows	• Higher susceptibility to wildfires and post-fire debris flows (larger magnitude)	• Lower wildfire susceptibility if precipitation is well distributed	• None	• Higher susceptibility to wildfires and post-fire debris flows (larger magnitude)	HIGH
ACTIVE LAYER DETACHMENT SLIDES (SHALLOW)	**DIRECT EFFECTS**					
	• More events due to permafrost degradation • Similar or higher magnitude	• Probably more events due to permafrost degradation • Similar or higher magnitude	• More events • Larger given the thickening active layer	• More events (regionally) • Events likely to gain mobility due to progressive entrainment	• Highly site-specific events	HIGH
	INDIRECT EFFECTS					
	• Higher susceptibility to wildfires and post-fire retrogressive thaw slumps due to accelerated permafrost degradations	• Higher susceptibility to wildfires and post-fire retrogressive thaw slumps due to accelerated permafrost degradations	• Lower wildfire susceptibility if precipitation is well distributed	• Slope destabilization due to increased toe erosion rates along creeks, rivers, and lakes (in particular thermokarst lakes)	• Highly site-specific events	HIGH

Table F - 1: Simplified Summary Chart of Landslide Response to Climate Change with Overall Predictive Uncertainty (continued)

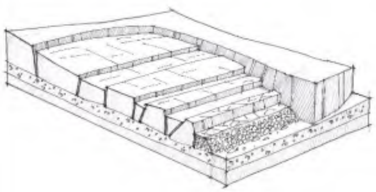
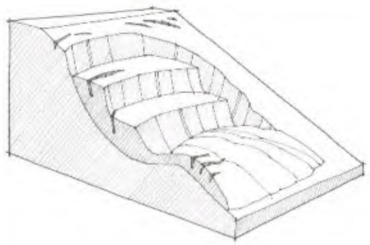
LANDSLIDE TYPE	GENERAL CHANGES IN TEMPERATURE AND PRECIPITATION			INCREASE IN RAINFALL INTENSITY (F-M)	CHANGES IN FREEZE-THAW CYCLES	OVERALL PREDICTIVE UNCERTAINTY[a]
	WARMER	DRIER	WETTER			
SPREADING FAILURES (SHALLOW OR DEEP-SEATED)	**DIRECT EFFECTS**					
	• Fewer events (if not offset by wetter conditions)	• Fewer events • Lower spreading rates • Possibly lower magnitude (depending on if truncated by stream)	• Possibly more events • Possibly higher magnitude	• Possibly none (depending on material characteristics, failure plane depth, hydraulic conductivity) • Possible surface modifications	• Probably none	HIGH
	INDIRECT EFFECTS					
	• In cohesive sediments, development of desiccation cracks and water ingress	• In cohesive sediments, development of desiccation cracks and water ingress	• Possible increase in movement rates by the toe undercutting by stream	• Possibly none	• Frost wedge development in permafrost environments	VERY HIGH
ROTATIONAL LANDSLIDES (DEEP-SEATED)	**DIRECT EFFECTS**					
	• Fewer events (if not offset by wetter conditions) • Lower spreading rates	• Fewer events • Lower spreading rates • Possibly lower magnitude (depending on if truncated by stream)	• Possibly more events • Possibly higher magnitude	• Possibly none (depending on material characteristics, failure plane depth, hydraulic conductivity) • Possible surface modifications	• Probably none	MODERATE
	INDIRECT EFFECTS					
	• In cohesive sediments, development of desiccation cracks and water ingress	• In cohesive sediments, development of desiccation cracks and water ingress	• Possible increase in movement rates by the toe undercutting by stream	• Highly site-specific events	• Frost wedge development in permafrost environments	HIGH

Table F - 1: Simplified Summary Chart of Landslide Response to Climate Change with Overall Predictive Uncertainty (continued)

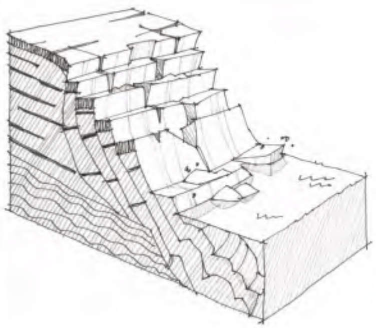
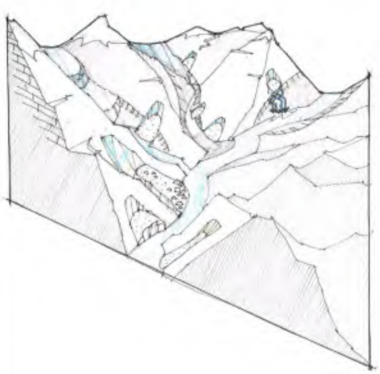
LANDSLIDE TYPE	GENERAL CHANGES IN TEMPERATURE AND PRECIPITATION			INCREASE IN RAINFALL INTENSITY (F-M)	CHANGES IN FREEZE-THAW CYCLES	OVERALL PREDICTIVE UNCERTAINTY[a]
	WARMER	DRIER	WETTER			
COASTAL LANDSLIDES	**DIRECT EFFECTS**					
	• Possibly fewer events due to enhanced evapotranspiration if not offset by wetter conditions and/or higher sea levels and complexity associated with wind pattern, sediment drift, mitigation works • Uncertain change in magnitude and movement rates	• Highly site-specific events	• More frequent events • Larger Landslides triggered by wave undercutting, sea level rise, increase in storminess	• Possibly fewer events but offset due to higher sea levels and complexity associated with wind pattern, sediment drift, mitigation works • Uncertain change in magnitude and movement rates	• Likely decrease in freeze-thaw cycles due to maritime climate associated with a possible reduction in rockfall frequency	MODERATE
	INDIRECT EFFECTS					
	• More rapid drying may affect movement rates in complex ways	• Cycles of drying and wetting may affect various source materials in different ways	• Salt crystal growth in chalk leading to decreased stability • Salt injection leading to increases in shear strength in clay slopes	• Highly site-specific events	• Highly site-specific events	MODERATE
LANDSLIDES IN THE CRYOSPHERE	**DIRECT EFFECTS**					
	• Mostly increases in the frequency and magnitude of high-alpine Landslides through glacial debuttressing and permafrost degradation	• Decreases in Landslide activity only where sediment is being depleted or colonized by vegetation	• More frequent events except where the source area rock or sediment is being depleted • Larger events except where sources are depleted	• Mostly increases in shallow Landslides in soil, but also some (more uncertainty) for large Landslides	• Likely increase in freeze-thaw cycles at higher elevation, especially in the shoulder seasons leading to more abundant rockfall and rockslide activity	HIGH
	INDIRECT EFFECTS					
	• Evolution of rockslides and/or rock avalanches into debris flows • Damming of receiving streams with upstream and downstream flooding • Changes in rivers from single thread to braiding or anastomosing • Increase in forest cover	• Possible development of desiccation cracks • Stress on forests, higher tree mortality, susceptibility to wildfires; stand opening can lead to higher rockfall runout	• Evolution of rockslides and/or rock avalanches into debris flows • Damming of receiving streams with upstream and downstream flooding • Changes in rivers from single thread to braiding or anastomosing	• Mostly increases in sedimentation rates in receiving rivers • Increased likelihood of damming of receiving rivers	• Highly site-specific events	MODERATE

Table F - 1: Simplified Summary Chart of Landslide Response to Climate Change with Overall Predictive Uncertainty (continued)

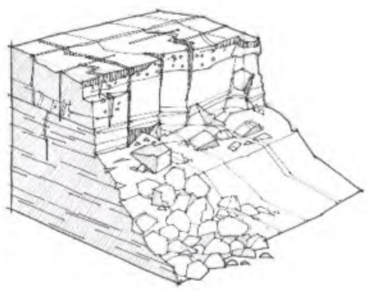
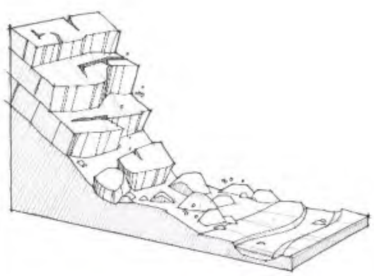
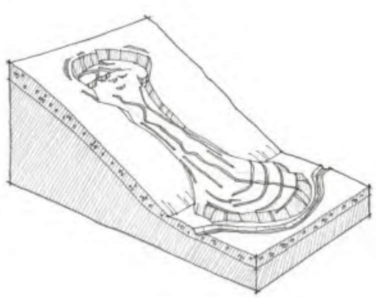
LANDSLIDE TYPE	GENERAL CHANGES IN TEMPERATURE AND PRECIPITATION			INCREASE IN RAINFALL INTENSITY (F-M)	CHANGES IN FREEZE-THAW CYCLES	OVERALL PREDICTIVE UNCERTAINTY[a]
	WARMER	DRIER	WETTER			
ROCKFALL AND ROCK SLIDES	**DIRECT EFFECTS**					
(a) Rockfall 	• Possibly more events due to increases in thermal expansion • More freeze/thaw cycles in now-cold areas	• Likely fewer events • Possibly smaller magnitude	• Likely more events • Possibly larger event	• Likely more events • Probably no change in magnitude	• Very likely more events • Probably no change in magnitude • Very likely increase in magnitude in permafrost regions with active layer thickening	VERY HIGH
	INDIRECT EFFECTS					
(b) Rock slides 	• More wildfires, more spalling of rock faces due to heat	• Highly site-specific events	• More freeze/thaw cycles	• Highly site-specific events	• Rock mass fracturing	EXTREME
EARTHFLOWS (DEEP-SEATED)	**DIRECT EFFECTS**					
	• Fewer events if not offset by wetter conditions • Likely lower movement rates if not offset by wetter conditions	• Very likely fewer events • Likely lower magnitude • Very likely lower movement rates	• Possibly more events • Possibly larger in supply-unlimited basins; smaller if supply-limited	• More events (regionally) if accompanied with sufficient antecedent moisture • Magnitude dependent on basin type	• Possibly higher weathering and debris supply in upper watershed • Magnitude changes dependent on rainfall pattern changes	HIGH
	INDIRECT EFFECTS					
	• Higher susceptibility to wildfires and hence changes in evaporation; ditto for changes in vegetation	• Higher susceptibility to wildfires and hence changes in evaporation	• Lower wildfire susceptibility if precipitation is well distributed	• Highly site-specific events	• Higher susceptibility to wildfires and post-fire debris flows (larger magnitude)	MODERATE

Table F - 1: Simplified Summary Chart of Landslide Response to Climate Change with Overall Predictive Uncertainty (continued)

LANDSLIDE TYPE	GENERAL CHANGES IN TEMPERATURE AND PRECIPITATION			INCREASE IN RAINFALL INTENSITY (F-M)	CHANGES IN FREEZE-THAW CYCLES	OVERALL PREDICTIVE UNCERTAINTY[a]
	WARMER	DRIER	WETTER			

NOTES:

Abbreviations: F-M = frequency-magnitude

[a] Uncertainty ranges from Low to Extreme, defined as follows:

- **Low**: Climate change effect (CCE) can be quantified reasonably well (<30% error) without detailed on-site instrumentation (DOI) such as piezometers, inclinometers, strain gauges, and general weather observations
- **Moderate**: CCE can be quantified (<50% error) without DOI
- **High**: CCE cannot be quantified well (>50% error) and in some cases require DOI over extended periods
- **Very High**: CCE relies fully on DOI and long-term studies
- **Extreme**: CCE cannot be reliably quantified even with DOI

Artwork credit: Derrill Shuttleworth

F.6 HAZARD CHAINS

F.6.1 EVOLVING KNOWLEDGE AND METHODOLOGIES

The combination of numerous recent occurrences of multihazards across the globe, and the emergence of new remote sensing tools to aid rapid and aerially extensive data collection (Clark et al. 2019), has resulted in a growing literature on multihazard assessment methodologies (Eshrati et al. 2019; NíChoine et al. 2015) and the development of numerical models to assess affected areas (Mergili et al. 2017; Tilloy et al. 2019; Worni et al. 2014; Zhang et al. 2016).

This new focus on hazard cascades—also called hazard chains—has arisen in part from disasters related to extreme weather (e.g., severe drought and fire, increased rainfall and intensity) caused by anthropogenic climate change (AghaKouchak et al. 2018). Another reason is widespread Landslide impacts following large earthquakes (Goda et al. 2018). In addition, in the European Alps and other high mountain areas around the globe, permafrost degradation is leading to concerns about Landslide-induced outburst flood and debris flow (Haeberli et al. 2017).

F.6.2 SEQUENCES OF HAZARD CASCADES

A hazard cascade may include:

- conditioning factors (e.g., climate change effects such as fire, precipitation, glacier change, sea-level rise);
- a trigger (e.g., earthquake, runoff drivers);
- complex Landslide processes (e.g., avalanche and/or debris flow);
- Landslide dams and their products (e.g., backwater flooding, outburst flooding); and
- downstream changes in the fluvial system (e.g., aggradation, lateral instability).

Table F - 2 provides examples of hazard cascades that have occurred historically in British Columbia.

F.6.3 CONSIDERING THE POTENTIAL FOR HAZARD CASCADES IN ASSESSMENTS

When presented with a hazard assessment, QPs must be cognizant of the potential for hazard cascades and must expand the project scope accordingly. Key aspects to be considered by QPs relating to hazard cascades are the probability of the originating hazard and the conditional probability of the hazard cascade materializing.

For example, where geomorphic flood scenarios (Jakob and Jordan 2001) can be envisioned, then the encounter probability at the proposed development site must be considered and evaluated against the appropriate hazard/risk threshold, with the appropriate threshold being governed by the scale of the development and the population exposure.

It should be noted that at lower levels of effort there may be greater uncertainty, and sensitivity analysis should be performed. If this uncertainty strongly overlaps with the acceptable threshold, then further work quantifying the hazard is required, or it may be prudent for the QP to use the cautionary principle and apply mitigation measures.

Table F - 2: Examples of Hazard Chains Occurring in British Columbia

YEAR	SITE	INITIAL EVENT	DESCRIPTION	SOURCE
2020	Elliott Creek, Southgate River, Bute Inlet	Slope collapse	• A glacially oversteepened and debuttressed slope collapsed into a lake, causing a catastrophic outburst flood that travelled 15 km to a main valley, then 9 km to Bute Inlet, triggering a submarine turbidity current.	Geertsema et al. (2021)
2019	Joffre Peak	Landslide	• Permafrost degradation was implicated in a complex Landslide and debris flood.	Friele et al. (2020)
2014	Mount Polley	Tailings dam collapse	• The failure and collapse of a large tailings dam led to a debris flow that contaminated a river and lakes.	Independent Expert Engineering Investigation and Review Panel (2015)
2012	Haida Gwaii	Earthquake	• An earthquake triggered Landslides, and the mass movement rate temporarily increased.	Barth et al. (2020)
2010	Mount Meager, Capricorn Glacier	Landslide	• Glacial over-steepening and debuttressing led to gravitational sagging, complex Landslide, Landslide damming and outburst flood, and long-term sediment pulse migration.	Guthrie et al. (2012) Roberti et al. (2017) NHC (2018)
2010	Testalinden Creek	Dam breach	• A small earthen dam breach led to debris flow, affecting a subdivision.	Higman et al. (2011) Tannant and Skermer (2013)
2007	Chehalis Lake	Landslide	• A Landslide triggered a tsunami wave in Chehalis Lake, destroying a forest service recreation site.	Roberts et al. (2013)
2003 2007 2009	Southern interior of BC	Post-fire Landslides	• Excess runoff in post-burn hillslopes triggered 36 Landslides, causing stream aggradation.	Vandine et al. (2005) Jordan and Covert (2009) Jordan (2015)
2005	District of North Vancouver	Landslide	• Heavy rainfall triggered a rapid fill-slope failure at the crest of an escarpment. Oversteepening of slopes and saturation due to surface water drainage into fill resulted in flow Landslides, retrogression, and downslope impacts.	Porter et al (2007)
1946	Vancouver Island	Earthquake	• An earthquake triggered multiple Landslides on Vancouver Island.	Mathews (1979)
Late 1500s	Adeane Point, Knight Inlet	Landslide	• A Landslide triggered a tsunami wave in Knight Inlet, destroying the First Nations village of Kwalate.	Bornhold et al. (2007)

F.7 POST-FIRE ASSESSMENTS

Post-fire Landslide Hazard and Landslide Risk assessments are being conducted more often in BC, due to the increase in wildfire frequency and severity associated with climate change (Haughian et al. 2012) and the continuing expansion of development into forested or grassy terrain.

Post-fire assessments can be executed pre-emptively, as most watersheds do eventually burn (albeit at different return periods), or they can be executed retroactively, once a fire has occurred. In the latter case, QPs can be more specific in their assessments, as the area burned and burn severity will be known. However, it should be noted that the next storm—even a moderate one—may trigger a debris flow or rockfall event, thus time is of the essence.

Post-fire hazard assessment methodologies are summarized in the *Land Management Handbook 69*, published by the BC government (Hope et al. 2015). When requested to conduct post-fire assessments, QPs must consult this handbook to inform themselves on conducting such assessments. It contains sections on identifying post-wildfire hazard and risks, risk analysis and mitigation, and a number of case studies.

In BC there are many small (<10 km^2), steep watersheds (ruggedness >0.6) that may be rocky and lack obvious sediment sources, and that have a low debris-flow frequency. This implies that there may not have been any debris flows observed since colonial settlement, so the perception of debris-flow hazard and risk may be very low. Complacency in this case could lead to a false sense of security, and with further densification these conditions may lead to major disasters.

Post-fire natural hazard assessments typically focus on debris flows and sometimes rockfall, both of which are affected directly by wildfires in BC and elsewhere. Post-wildfire debris slides that initiate due to root-strength losses may not occur for several years after the fire. A vast body of literature exists on the subject of post-fire debris flows that should be consulted; however, caution is warranted when applying results from outside of BC to wildfires within BC terrain, ecosystems, and climate. Post-fire debris flow and rockfall assessments require substantial expertise and should thus only be conducted by specialists in the field.

In an area where fire is a normal part of the geomorphology with a return frequency of, for example, 1:100, the long-term debris-flow frequency from the historic record captures the post-fire frequency. In situations like this, the fire acts like the trigger, creating the conditions for an imminent event. In a proposed development, if the potential for the debris flow has been recognized and an appropriate F-M model determined, and if mitigation has been appropriately designed, then post-fire debris flow will be accounted for. However, if this is an existing development that lacks structural mitigation for debris flow or rockfall, then an "emergency" post-fire assessment will be required to evaluate the risk, and emergency management measures may be called for.

With increasing wildfire frequency and severity combined with the vast number (thousands) of debris flow-prone alluvial fans in some developments in BC, the need for post-fire hazard assessments is increasing rapidly. These assessments may need to be carried out very quickly after a fire, as even a moderate (1- to 2-year return period) rainstorm can trigger post-fire debris flows over the two years after the fire, which differs fundamentally from non-fire-related debris flows.

Figure F - 6 shows debris-flow triggering rainfall intensity-duration thresholds for a global dataset (Guzzetti et al. 2008), with some examples of post-fire debris-flow triggering thresholds for various locations in the United States. It demonstrates clearly that post-fire debris-flow initiation intensities are much lower than for debris flows unassociated with wildfires. If a severe wildfire in a watershed susceptible to debris flow coincides with a particularly heavy rainstorm (e.g., a 20-year return period or higher), extreme Consequences can be expected.

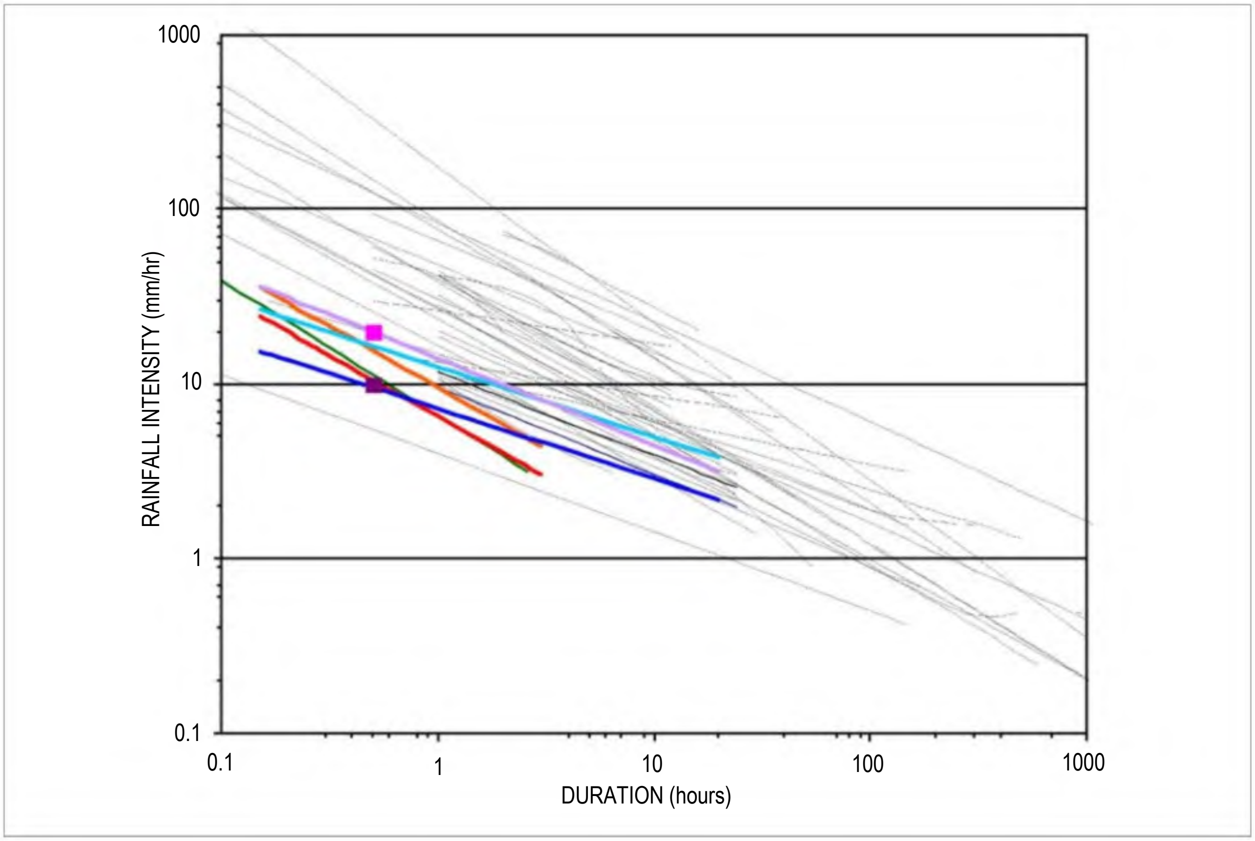


Figure F - 6: Comparison of a global dataset of rainfall intensity-duration thresholds for shallow Landslide initiation (grey lines), juxtaposed with post-fire thresholds from Colorado, South Dakota, and New Mexico

NOTES: Adapted from Cannon et al. (2008)

F.8 LANDSLIDE HAZARD MAPPING

F.8.1 INTRODUCTION

Currently, there are no Landslide Hazard mapping standards in place in Canada. This contrasts with practices in other developed nations, or even with other natural hazard-related processes in BC. For example, floods are addressed in the professional practice guidelines titled, *Legislated Flood Assessments in a Changing Climate in BC* and *Flood Mapping in BC* (Engineers and Geoscientists BC 2018 and 2017a, respectively), and snow avalanches are covered in the *Technical Aspects of Snow Avalanche Risk Management* guidelines (Canadian Avalanche Association 2016).

This appendix introduces a standardized methodology that applies to rapid Landslides, for which the hazard potential is characterized by impact forces or return periods, rather than creeping Landslides, which are characterized differently. Those types of hazards must be mapped by delineation and indication of movement rates, which are related to the destruction of structures situated on top of a creeping Landslide.

Hazard maps are a vital tool for decision making. Producing meaningful hazard maps requires consideration of event frequency, extent, and intensity. Intensity can be expressed primarily as impact force or impact pressure, or a proxy of either.

Hazard mapping should contain two components:

1. Individual hazard scenario maps, that is, maps that show the runout and intensity for specific

scenarios, which could be for return periods or for mitigated versus unmitigated versions.

2. Composite hazard maps that unite all scenarios in one map by aggregating the results.

Note that individual hazard scenario maps show judgment-based hand mapping or model outcomes without interpretation for different return periods. Those are typically not created for public policy decision-making purposes, but may be consulted for site-specific projects.

F.8.2 TYPES OF LANDSLIDE HAZARD MAPPING IN BC AND THEIR APPLICATION

Landslide-related maps show the spatial relationship between Landslide characteristics and processes and the surrounding natural and built environment. Depending on the study, they might support land-use decision making, engineering design, emergency management decisions, or public communication.

The type of Landslide-related map, or collection of maps, which the QP elects to accompany the assessment will depend on the project scope, purpose, and objectives.

Landslide-related maps can be grouped into four categories (Hervás and Bobrowsky 2009):

- inventory maps;
- susceptibility maps;
- hazard maps; and
- risk maps.

The following subsections provide an overview of each map type, including the associated historical context in BC.

F.8.2.1 Inventory Maps

Landslide inventory maps show past and current Landslide occurrence (Jackson et al. 2012). These maps are generally factual in nature (Fell et al. 2008), with the main purpose of showing the location, type, and abundance of Landslides in a region. Symbology used to represent the inventory depends on the map scale, where Landslide features can be shown as points, lines, polygons, or feature outlines (RIC 1996).

The generation of Landslide inventories in BC has evolved over time from paper-based mapping, using a combination of site record reviews, field surveys, and aerial photograph interpretation, to the processing and analysis of remotely sensed digital terrain information with GIS (Hervás and Bobrowsky 2009).

Possibly the first Landslide inventory and assessment in BC was generated in 1897 by Robert Stanton, a British civil engineer, who mapped Landslides crossed by the Canadian Pacific Railway along the Thompson River approach slopes (Stanton 1897). Engineering geology investigations carried out across BC following this work throughout the early- to mid-1900s included mapping of Landslides and Landslide deposits to support development decisions (Allan 1952; VanDine 1991); however, practices were generally not systematic. This period represented the growing practice of engineering geology and Geotechnical Engineering in BC (VanDine 1983; VanDine 1991).

Systematic Landslide inventory mapping in BC has its origins in surficial geology mapping programs, which began in the 1940s and by the 1960s included mapping of landforms in addition to surficial units (RIC 1996). By the early 1970s, the Geological Survey of Canada and the BC Ministry of Environment had developed and formalized a systematic terrain classification system (1999), where modern geomorphological processes such as Landslides were mapped alongside surficial geologic units; this system was used to inform land-use and development decision making. Over the 1970s and 1980s, terrain mapping was used to map large areas of the province at scales ranging from 1:50,000 to 1:250,000 (ELUCS 1976; RIC 1996). In parallel, members of the Geological Survey of Canada and academia began to carry out mapping and investigation of Landslides across broad regions in a variety of mountainous terrain in BC (O'Loughlin 1972; Eisbacher 1977; Clague 1978; Matthews 1979; Eisbacher and Clague 1980; Clague 1984). This work represents early research into BC Landslide processes.

Systematic Landslide inventory mapping continued to form a key foundational element of Landslide Hazard assessment from the 1980s to the present, with several studies being completed across the province (Jordan 1987, 2000; Gimbarzevsky 1988; VanDine and Evans 1992; Golder 2006; Blais-Stevens 2007). Investigations since the late 1990s have increasingly applied computational tools, such as GIS and geospatial databases, to support mapping (Blais-Stevens et al. 2016). The most recent techniques use algorithms for automated mapping of remotely sensed data and can generate Landslide polygons inventories across broad regions (Barth et al. 2020), including at the provincial scale (Pichierri et al. 2019).

The inventory mapping described above has been conducted at a small, or regional, scale (1:20,000 or less). These products will form a basis for background review, but for any Landslide Assessment the study area affecting the site will need to be delimited, and a detailed inventory (>1:20,000 scale) conducted within. The inventory will need to document all known and previously mapped features, and should also identify hazards not evident at the regional scale, such as steep-slope source areas for shallow landsliding and rockfall, and the potentially affected areas downslope. Of particular concern are anthropogenic features in the study area, primarily roads, especially fillslopes and road drainage (e.g., Hummingbird Creek 1997), but this may also include dams (e.g., Testalinden Creek 2010) and various landforms produced by mining.

In BC, forest service roads are ubiquitous in the landscape upslope of proposed development areas. Many older roads were constructed before modern construction standards (i.e., pre-1993 *Forest Practices Code*) and have been abandoned. Legacy roads typically have road sections with poorly constructed fills perched on steep slopes. Regardless of age, the imposition of road networks on the landscape alters hillslope hydrology, and this may lead to instability (e.g., Cherry Ridge 2012). Further, as per the *Forest and Range Practices Act*, drainage structure design is for a 1:10-year to 1:50-year flood for temporary roads, and a 1:100-year flood for permanent roads, and this implies potential for failure at frequencies relevant to human residency (1:500 or less). These potential situations need to be identified and mapped, and the Consequences to the proposed development considered.

Inventory maps are key to informing QPs as a starting point for Landslide Assessments, to understand the distribution of Landslides in the area, from which inferences can be made as to the susceptibility of Landslides for specific geomorphic or geological conditions. They are also very useful to inform region-wide Landslide Risk prioritization studies, once the potential Consequences have been documented and hazard levels assigned to the documented Landslides.

F.8.2.2 Susceptibility Maps

Landslide susceptibility maps show the probability or likelihood of Landslide occurrence in an area (Hervás and Bobrowsky 2009). Susceptibility mapping involves delineating and rating mapping units (Hansen 1984) according to their Landslide susceptibility, which is dependent on the topography, geology, geotechnical properties, climate, vegetation, and anthropogenic factors (Fell et al. 2008). Susceptibility ratings can be represented as qualitative (e.g., low, medium, high) or quantitative (e.g., 0 to 1) values. These maps have typically formed a basis for defining areas where special conditions on development are required in a jurisdiction (RIC 1996).

Landslide susceptibility mapping in BC has its origins in terrain stability mapping, which includes mapping zones of potential initiation of slope failure (BCMOF and BCMOE 1999). In the 1970s and 1980s, the BC Ministry of Transportation and Infrastructure carried out several pilot terrain stability mapping projects to support land use decision making in unincorporated areas, over which they have responsibility (Buchanan 1977; Haughton 1978). In parallel, terrain attribute studies (Rollerson and Sondheim 1985; Howes 1987) were being carried out to inform better terrain stability mapping approaches, and represent early research into the relationship between terrain attributes and Landslide occurrence in BC. Refined versions of the terrain stability mapping system (Schwab and

Geertsema 2009) have been used widely across the province for Landslide susceptibility mapping since the 1990s.

Since the 1990s, Landslide susceptibility mapping has progressively evolved from predominately paper-based to computer-based mapping (Niemann and Howes 1992; Pack et al. 1998; Lier et al. 2004; Blais-Stevens et al. 2012; Minerva Intelligence 2020). Improvements in GIS, remote sensing, and more complete spatial databases of terrain factors has facilitated the generation of higher resolution and/or larger scale assessments (Goetz 2012; Bobrowsky and Dominguez 2012) and the application of more advanced analytical techniques (Shano et al. 2020). Given these advancements, large-scale or regional-based Landslide susceptibility studies have increased in number over the past two decades (Chung et al. 2001; BGC 2012; KWL 2013). Over the past decade, these approaches have also benefitted from advances in numerical modelling that have been used to more explicitly consider Landslide processes, such as run-out, in regional susceptibility mapping (BGC 2019; Stantec and Palmer 2020).

Landslide susceptibility maps are useful as direct input to risk-prioritization studies, as they allow a designation of hazard without the necessity of detailed site-specific studies. Therefore, they should be generated, particularly as part of linear infrastructure projects.

F.8.2.3 Hazard Maps

Landslide Hazard refers to the probability of Landslides of a particular type and magnitude in a given location occurring within a reference time period (Hervás and Bobrowsky 2009). Landslide Hazard mapping therefore shows the spatio-temporal probability of a specific Landslide and associated process, such as the occurrence probability, run-out probability, or hazard intensity. Landslide Hazard zones may be rated with qualitative or quantitative values, and represented as feature outlines, polygons, or grids (Fell et al. 2008). For municipal developments in BC, Landslide Hazard maps are typically used for zoning and bylaw enforcement.

Systematic Landslide Hazard mapping for land-use and development planning in BC began in the early 1980s (Thurber Engineering 1983; 1987). This work built on the Landslide inventory and mapping completed during the previous decade, and evolved in part due to the requirement for geotechnical engineers to certify developments as “safe for intended use” as stipulated in the 1979 BC Municipal Act (Section 734.2) (Gerath 1992). Work throughout this decade mostly focused on Landslide Hazard along transportation corridors (Thurber Engineering 1989; Slaymaker 1990).

For example, in the 1990s through the mid-2000s, the Fraser Valley Regional District (FVRD) commissioned Thurber Engineering to map hazard and risk throughout many of the electoral areas in their jurisdiction. These mapping efforts typically identified polygons in the following classifications:

- No apparent hazard (NAH): no further geotechnical report required unless a hazard is suspected or identified by the Building Inspector
- Potential hazard (PH): requires geotechnical hazard advice in support of development or building permit applications
- Significant hazard (SH): requires geotechnical hazard advice in support of all development and building permit applications

Community hazard zoning work in the FVRD has continued (Cordilleran 2009, 2012; Cordilleran and Braun 2014).

Similarly, Baumann Engineering (1993) produced air photo-based hazard mapping for the Squamish Lillooet Regional District (SLRD), for the corridor between Pemberton and D’Arcy, BC. This was traditional terrain mapping, classifying parent material, surface expression, and active process affecting each polygon. Polygons were colour coded to reflect management response as follows:

- Red: development unlikely due to high hazards
- Yellow: further geotechnical advice required
- Green: generally considered safe with respect to Landslides

The colour-coded stoplight approach was deemed a useful and logical form of communication. This mapping is available on the SLRD website.

Possibly the first comprehensive, very detailed, higher-class level-of-effort Landslide Hazard assessment for development planning and residential zoning in BC was conducted for the Cheekye fan in Squamish, BC, which was completed in 1993 (Thurber-Golder 1993; Sobkowicz et al. 1995). This work included detailed investigation of existing and future basin hazards (i.e., "the Cheekye Linears"); subsurface investigation of alluvial fan deposits; identification of the largest probable events (i.e., the "Squamish Unit" and the "Garbage Dump Debris Flow"); and preparation of an F-M model. The main outcome included a land-use zoning map that accounts for Landslide impact probability, intensity, and potential risks.

Around the same time, practitioners and government agencies were beginning to establish hazard acceptability thresholds for development approvals (Morgan 1986; Cave 1992, 1993), which established the goals for hazard assessments throughout the 1990s, and still form the basis for best practices today.

Since these early studies, Landslide Hazard mapping techniques have progressively improved, mostly due to improvements in base data availability and quality (e.g., high-resolution LiDAR-based or SfM topography), numerical modelling, Landslide- and climate-monitoring techniques, and change detection from remote sensing (e.g., LiDAR, InSAR, SfM). Again, at the forefront is work on the Cheekye fan, where further historical geomorphic analysis (Friele et al. 1999; Clague et al. 2003; Friele and Clague 2005; Jakob and Friele 2010) allowed for refinement of the F-M model (Jakob and Friele 2010) and flow modelling calibrated to the documented volume and spatial distribution of the last catastrophic, channel-overtopping event (Jakob et al. 2012). This work is now being used in conjunction with Consequence assessment to design structural mitigation measures.

Finally, gaining in importance, especially for higher-level planning and communication to the public, are "composite" or "multiple" hazard maps that convey a complete picture of the natural hazards of varying magnitude and frequency affecting a study area. Composite hazard-rating maps show the maximum extent of all hazard scenarios and portray areas most likely to be affected. Multi-hazard mapping is an educational and analytical tool for appreciating the full risk-spectrum affecting communities, and may aid emergency preparedness planning.

These types of maps should be generated, especially in cases where Local Governments require tools that can be translated into land-use planning but can also inform the design of appropriate mitigation measures.

F.8.2.4 Risk Maps

Landslide Risk maps show the probability of a particular loss as a result of Landslide impact (Hervás and Bobrowsky 2009), where the loss can include anything of value to society or to the owner of the risk. Landslide Risk maps depend on the Elements at Risk, including their temporal and spatial probability, and vulnerability (Fell et al. 2008). Risk maps typically show Elements at Risk rated with quantitative or qualitative variables, and are snapshots in time based on an understanding of the current or future conditions. Landslide Risk maps can help inform risk mitigation measures, emergency management, and application of risk management regulations (Hervás and Bobrowsky 2009).

The first quantitative Landslide Risk assessment for municipal development planning in BC was completed in 2007 for the District of North Vancouver (Porter et al. 2007). Risk tolerance policy developed and applied for this project was then used by several other jurisdictions in BC through the late 2000s and 2010s for Landslide Risk assessment and mapping projects (Thurber Engineering 2019). Possibly the most comprehensive risk assessment for development planning in BC to date was completed in 2019 (BGC 2019), which was built on best practices developed over the past decade.

In the early 2010s, the first multi-site Landslide Risk prioritization mapping studies (BGC 2019) were carried out in BC. This work aims to identify, map, and prioritize hazard-susceptible areas based on the principals of risk, with the purpose of supporting Local Governments with resource allocation planning. To date, large areas of BC spanning over 200,000 km^2 have been mapped.

F.8.3 HAZARD INTENSITY MAPPING

Landslides can be characterized by their intensity, and defined as a set of quantitative or qualitative spatially distributed parameters, which can determine the potential of a given Landslide phenomenon to cause damage. Determination of potential intensity is an intermediate step in Landslide Risk mapping (Hungr 1997).

Numerical computer model outputs can include grid cells showing the velocity, depth, bounce height (for rockfall), and extent of impact. These variables describe the intensity of an event. They provide no information on the likelihood of a specific location being impacted. The model outputs can be combined to show impact force, which relates to structure vulnerability, across the hazardous landform for each model scenario.

Impact force (F_I) is defined as the combination of velocity (v), area of impact (A) and bulk density of a particle or fluid (debris flows) (ρ) shown in the following equation:

$$F_I = \rho \, A \, v^2 \qquad [12]$$

The area of impact represents the area of the object that is impacted or the portion thereof. For this level of study, geohazard depth or thickness from modelling results is used as a proxy for the height of the area, and the impact force is then represented as an impact force per unit width (in this case, 1 m).

The impact force results are then binned to illustrate what their impacts may be. Each impact force range has a description which is specific to different Landslide processes. Table F - 3 provides an example for debris flows.

Table F - 3: Example of Impact Force Ranges Calculated For Debris Flows

IMPACT FORCE [a] (kN/m)	DESCRIPTION OF DEBRIS FLOW
<1	• Slow-flowing, shallow, and deep water with little or no debris • High likelihood of water damage • Potentially dangerous to people in buildings in areas with higher water depths
1 to 10	• Mostly slow-flowing water, but potentially fast-flowing, shallow, or deep water with some debris • High likelihood of sedimentation and water damage • Potentially dangerous to people in the basement or on the first floor of buildings without elevated concrete foundations
10 to 100	• Fast-flowing water and debris • High likelihood of structural building damage and severe sediment and water damage • Dangerous to people in the basement or on the first floor of buildings • Replacement of unreinforced buildings likely required
>100	• Fast-flowing debris • High likelihood of building destruction • Very dangerous to people in buildings, irrespective of floor

NOTE:

[a] The impact force results are binned to illustrate what their impacts may be.

F.8.4 COMPOSITE HAZARD MAPS

Hazard quantification combines the intensity of potential events and their respective frequency. Areas with a low chance of being impacted and at low intensities are designated very differently from areas that are impacted frequently and at high intensities. For the latter, the resulting geohazard risk is substantially higher and development must be more restricted than for the former.

An impact intensity probability (P_I) geohazard mapping scheme was created that consists of two main components:

- the intensity expressed by an impact force per metre flow width; and
- the frequency of the respective events.

The underlying equation is as follows:

$$P_I = v^2 \times \rho_f \times d_f \times P(H), \qquad [13]$$

where $\mathbf{v}$ is flow velocity (m/s);
d_f is the fluid's flow depth (m);
ρ_f is the fluid or particle density (kg/m^3) to obtain a unit of force per metre flow width for the three left terms in equation 13; and
$P(H)$ is the annual probability of the geohazard.

The unit of P_I is then Newton per metre per year (N/m per yr). This is applicable to Landslides of the rapid flow and fall types, such as debris flows and rockfall, respectively.

Equation 13 can be translated into a simplified matrix for public use, as per Figure F - 7. Here, the geohazard intensity describes the intensity of the event from "low" to "extreme," and zones indicate the respective hazard. The overarching principle is that low return periods (high frequencies) combined with high or very high hazard intensities should result in the highest overall hazard. The opposite is applicable to high Landslide return periods (low frequencies) and low or very low hazard intensities.

The advantage of this mapping type is that a single map codifies which areas are exposed to what hazard. Given that impact force is a surrogate for the destructiveness of a geohazard, P_I maps are proxies for risk, assuming Elements at Risk are present in the specific hazard zones. Therefore, their application and regulatory interpretation, in many cases, may replace quantitative risk assessments.

The map type is called a composite hazard map because it is created by numerically overlaying all hazard scenarios that have been considered or modelled. For example, if a 10 to 30-year, 30 to 100-year, and 100 to 300-year return period event is modelled, the intensities ($v^2 \times \rho_f \times d_f$) are being determined for each cell and multiplied by their respective frequency class (i.e., 0.1 to 0.03, 0.03 to 0.01, 0.01 to 0.003) in GIS software. Each coloured area can then be assigned a specific regulatory prescription depending on proposed new or existing development. The interpretation occurs through examining the raw results, which are highly pixilated, and manually smoothing the outlines to avoid undue exactness resulting from the mathematical procedure.

Interpreted hazard maps showing impact force frequency (IFF) values can be developed for each return period class at all locations within the study area. In some cases, individual properties may have been artificially raised and are thus less prone to flood or debris flood impact. Such properties would need to be identified at a site-specific level of detail, for example, if the owner intends to subdivide or renovate the property and ask for an exemption to existing bylaws.

Other elements can be added to a composite hazard rating map, such as bank erosion, where applicable to debris flows. Similarly, for rockfall, the bounce height could be added by contouring expected bounce height.

Figure F - 8 shows the interpreted version, where small nuances from modelling are smoothed to avoid the illusion of exactness (BGC 2020).

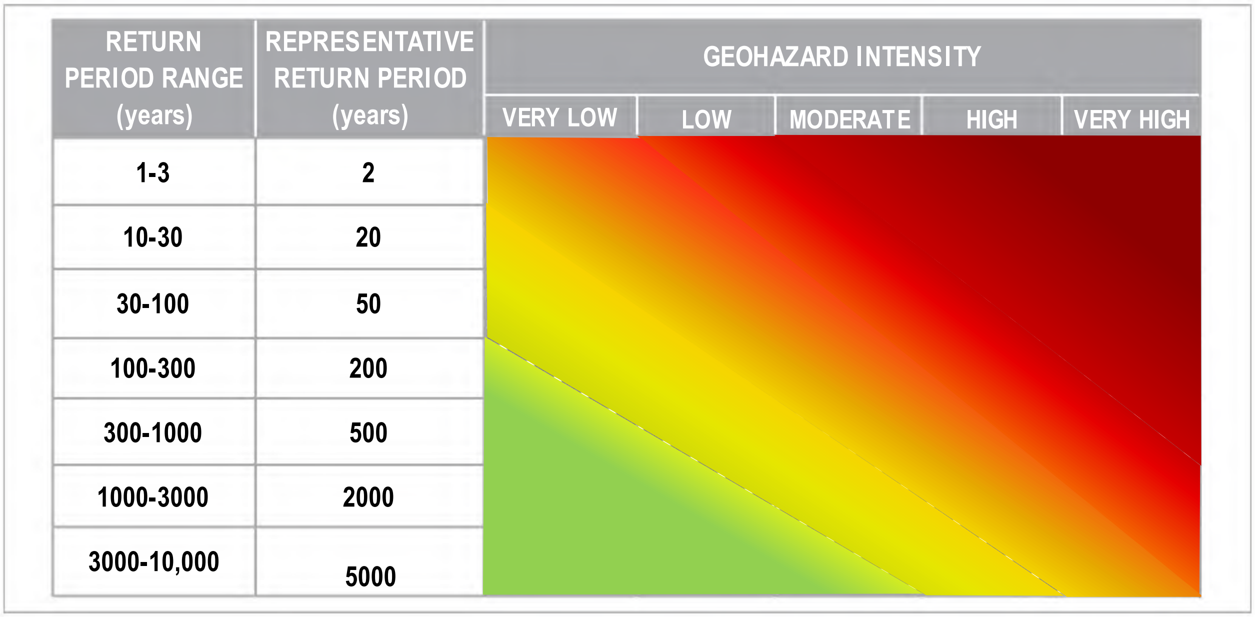


Figure F - 7: Simplified geohazard impact force frequency matrix.

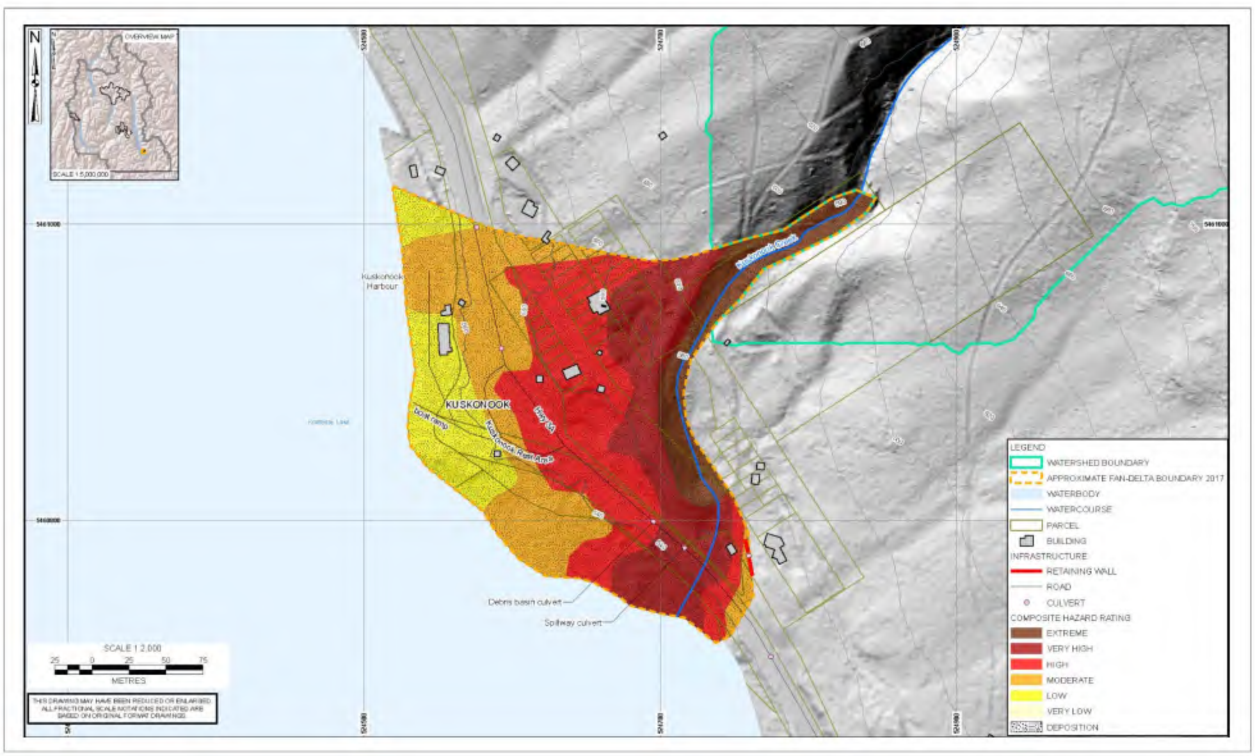


Figure F - 8: Composite debris-flow hazard map for Kuskonook Creek, Regional District of Central Kootenays

NOTES: From Regional District of Central Kootenays (BGC 2020), with permission.

F.8.5 POLICY TRANSLATION

It is useful for Local Governments to translate the findings from a composite hazard map into land use policy. This avoids onerous interpretation of the hazard map by non-experts in the field and, in many cases, preclude the necessity for quantitative risk assessments that add a layer of complexity to Landslide Assessments.

Figure F - 9 provides an example for how the findings from a composite hazard map can be extracted and implemented in policy. Table F - 4 provides background on the meaning of the different columns.

Table F - 4: Key to Information Pertaining to Figure F-9

COLUMN	INFORMATION
1	Level of hazard, including standing water with its specific hazard profile
2	Expected type and frequency of damage
3	Likely hazard Consequences for typical wood-frame structures, as reinforced concrete structures are more resilient to impact forces
4	The potential for injury and loss of life
5	Types of policies that may be considered by the Local Government for different hazard levels
6	Calculated ranges for the intensity-frequency classes in order-of-magnitude groups
7	Likely probability of death of an individual (PDI) values, again assuming standard wood frame structures
8	Whether a quantitative risk assessment (QRA) should or should not be conducted
9	Circumstances under which a development permit application could be granted
10	Landslide types to which the proposed system applies

HAZARD DESCRIPTOR	EXPECTED DAMAGE AND FREQUENCY	HAZARD AND CONSEQUENCE DESCRIPTION GIVEN IMPACT TO STANDARD (WOOD FRAME) BUILDING	INJURY OR LOSS OF LIFE	POLICY PRESCRIPTION FOR NEW OR EXISTING DEVELOPMENT PERMIT APPLICATIONS	IMPACT FORCE PROBABILITY ($Nm^{-1}yr^{-1}$)	APPROXIMATE CORRESPONDING PDI RANGE (highly dependent on vulnerability and occupancy)	QUANTITATIVE RISK ASSESSMENT RECOMMENDATION FOR FUTURE DEVELOPMENTS	EXIST. DEVELOP. PERMIT APPLICATIONS	FUTURE DEVELOP. PERMIT APPLICATION	TYPICAL PROCESS TYPE RANGE
STANDING WATER	Any frequency to	• Hazard can occur at any return period and can lead to life loss in extreme cases and major building damage	Only under exceptional circumstances (e.g. flooding of buildings in depressions without warning)	On-site protection or building resiliency measures	N/A	Variable	Yes, if credible life loss potential	FCL based on maximum water depth for the Q200 clearwater flood	Only if proponent can build above FCL and no risk transfer	Floods/Debris Floods
VERY LOW	Low to moderate frequency to	• Hazard is very rare or of minor intensity and does not constitute a credible life loss risk but can cause nuisance building damage			<1	$<10^{-5}$	Typically not required	FCL based on highest modelled flows for the Q200 debris flood (allowing for sediment deposition where applicable)		Debris Flows; Landslides
LOW		• Hazard is rare or of moderate intensity and is unlikely to lead to loss of life, but will cause substantial building damage			1 to 10	10^{-4} to 10^{-5}			Hazard should be reviewed if substantial changes occur in hazard areas	
MODERATE	Low to high frequency to	• Hazard likely occurs within a person's lifetime or of substantial intensity and may lead to loss of life and considerable building damage	FATALITY	Usually only permittable with global mitigation	10 to 100	10^{-3} to 10^{-4}	Required	Conditional <25% floor space increase	Only if PDI risk <1:10,000, and group risk can be reduced to tolerable levels	
HIGH	Moderate to high frequency	• Hazard occurs frequently or with very high intensity and is likely to lead to loss of life and requires building reconstruction	FATALITY		100 to 1,000	$>10^{-3}$		Only with mitigation to "yellow"		
VERY HIGH		• Hazard occurs very frequently or with extreme intensity and is very likely to lead to loss of life and total building destruction	FATALITY		>1,000			Not approved as benefit-cost ratio for mitigation typically very low		

Figure F - 9: Example of how a composite hazard map can be translated into policy

NOTES: Example only; such a table must be customized for the specific Approving Authority's needs and embedded within existing policies

Abbreviations: ALARP = as low as reasonably practicable; FCL = Flood Construction Level; PDI = annual probability of death to an individual

F.9 REFERENCES – APPENDIX F

F.9.1 REFERENCES

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APPENDIX G: STRATEGIES FOR UNCERTAINTY REDUCTION

This appendix supports Section 3.4 Uncertainties, Limitations, and Qualifications of a Landslide Assessment of these guidelines, specifically Section 3.4.2 Identifying Uncertainty.

Uncertainty is an inherent part of Landslide Hazard and Landslide Risk assessments. This necessitates that uncertainty be identified, reduced when practical, clearly communicated, and accommodated.

G.1 REDUCING KNOWLEDGE-SOURCE UNCERTAINTY

Knowledge-source uncertainty arises from limited information or understanding about a model or process, limits on the accumulated experience of the assessor, and limitations of the underlying data.

Landslide Hazard assessment, Landslide Risk assessment, and related aspects of mitigation involve reducing knowledge-source uncertainty in some or all of the following ways:

- Identify knowledge gaps early in the assessment process and seek targeted information. This is an example of the monitoring and review element in the Landslide Risk management process.
- Apply independent methods in the same assessment; for example, vegetation analysis, topographical assessment, and/or combining empirical and numerical models to estimate runout.
- Seek independent expert opinions of hazard and risk, or access guidance from other sources, such as assessment and decision aids.
- Stay informed about advances in understanding regarding sources of uncertainty, in particular climate change and its effect on Landslide Hazard and Landslide Risk.

G.2 CONSIDERING NATURAL UNCERTAINTY

Natural uncertainty is inherent to a system due to natural variability or randomness (e.g., the difference in causes and triggers of Landslides).

While natural uncertainty cannot be reduced, it must be considered along with any knowledge-source uncertainty in Landslide Hazard and Landslide Risk assessments. However, fundamental limitations in knowledge of Landslide mechanics, size, causes, and triggers may result in frequencies, magnitudes, intensities, or runouts that exceed levels stated in thorough assessments.

Following are strategies for considering natural uncertainty and reaching appropriate decisions and designs for mitigation (see also the discussions of risk tolerance and acceptable risk in Section 3.3.4 Weighing Types of Risk Assessment).

- **Factor of Safety (FS)**: For mitigation works, the FS is the ratio of the design strength (or structural capacity) to the design load. Higher ratios are safer in that they allow for greater uncertainty in the load and design strength, including variations over time and space.
- **Statistical analysis**: When the statistical distribution of a random variable used in Landslide Risk or Landslide Hazard assessments is modelled, 50% of its values will be less than or equal to the median (which is close to the mean or expected value for approximately symmetric distributions). Hence, the median has a non-exceedance probability of 0.5.

  In Landslide Hazard or Landslide Risk assessments with higher uncertainty, it may be advantageous to apply a higher non-exceedance probability to a particular variable. For example, a non-exceedance probability of 0.8 may be applied for runout estimation, which means that only 20% of the paths in the range have relatively longer maximum runouts. When Landslide Hazard or Landslide Risk is modelled as a statistical distribution, such as in Monte Carlo simulations, a higher non-exceedance probability corresponds to lower Landslide Hazard or Landslide Risk.

- **Design margin**: Design margin refers to the additional caution required in determining the design strength for mitigation works due to the residual uncertainty associated with Landslide Risk assessments. For example, the uncertainty associated with climate change effects on debris flows may call for a greater margin of safety for risk treatment.

  Since the uncertainty cannot be fully known or quantified, it is sometimes managed by adding a design margin in the design of mitigation works. Similarly, design margin could be provided for by use of flexible or modular approaches, with additional mitigation elements added should future scientific advances demonstrate that a higher degree of safety is desirable.

- **Team decision-making**: Teams of experts can seek a consensus, or risk options can be vetoed for conservative reasons, thereby accounting for uncertainty. Such team approaches can also examine whether the results of a Landslide Assessment or proposed mitigation measures are considered overly conservative.

G.3 COMMUNICATING UNCERTAINTY

Identifying and communicating uncertainty is an important part of Landslide Hazard and Landslide Risk assessments. Hence, it should be explicitly communicated to the risk owner and others involved in assessing hazard and risk and should be documented in the Landslide Assessment Report.

Uncertainty in a qualitative variable can only be expressed qualitatively; uncertainty in a quantitative variable can be expressed quantitatively or qualitatively.

Methods to communicate qualitative and quantitative uncertainty include the following:

- Use a finite ordered list of levels or classes, in which fewer classes (i.e., lower resolution) implies greater uncertainty.
- Describe or display the applicable range of a variable. For example, rockfalls that range in size can be displayed graphically with a box and whisker, or with a rectangle or ellipse (displayed lengthwise or widthwise).
- List possible scenarios (i.e., a debris avalanche may not reach the Element at Risk or continue to bulk and increase in volume and width).
- Express qualitative uncertainty in terms of confidence levels, in which high confidence is associated with low uncertainty and vice versa.
- Because expressing quantitative uncertainty requires error estimation (e.g. determining the accuracy of measurements through an analysis of equipment and observer bias), express it as a confidence interval, as in traditional statistical analysis. Most statistical extreme value packages allow plotting of confidence or prediction limits at a specified percentage.

APPENDIX H: METHODS FOR LANDSLIDE RISK REDUCTION

H.1 INTRODUCTION

In many instances, the motivation for a Landslide Assessment is to provide appropriate mitigation solutions that can render the risk to an existing or proposed development tolerable. This section is specifically targeted towards Qualified Professionals (QPs) whose scope of work includes protection of developments from Landslide impacts.

If an unacceptable Level of Landslide Safety is identified, the QP may be required to recommend measures to reduce Landslide Hazards and/or Landslide Risks. Measures can be deemed non-structural, such as Covenants or relocation of proposed buildings, or structural, such as stabilization or protective works. Ideally, both types of measures should be combined for existing and proposed developments, to achieve optimal risk reduction.

H.2 COMMUNICATING RISK-REDUCTION DECISIONS

The QP is responsible for discussing both non-structural and structural risk-reduction measures with the Client and the Local Government, to ensure there is adequate understanding to allow for informed decision-making, particularly when the operation and maintenance of the mitigation works or warning systems will be the responsibility of the Local Government.

The QP should also estimate and clearly explain residual risks, or those that remain after any recommendations have been implemented. Two principal sources of residual risk exist: 1) the portion of the originally estimated unmitigated risk; and 2) the non-estimated risk associated with a return period beyond that specified in the level of effort tables (see Appendix B: Landslide Assessment – Determining the Level of Effort). Where a local jurisdiction has a policy or other documents detailing different Levels of Landslide Safety, those take precedent.

Most studies conducted by the authors of these guidelines have indicated that the highest life-loss risk is associated with the lowest return period resulting in one or more fatalities. Therefore, unless there is a process change at higher return periods (for example, from rockfalls to rock avalanches), the total risk is only marginally affected by the unquantified risk for such higher return-period events. As a minimum, the QP should discuss this limitation with the Client or Approving Authority.

The QP should also be aware that achieving consistency of accepted residual risk levels at mitigated sites across varying jurisdictions, while desirable, is challenging, given that mitigation funds may be limited. The QP should also consider that variations in approvals for accepted or grant-funded mitigation scenarios may transfer liabilities to the Approving Authority; therefore, any known variations should be discussed with the Approving Authority early on, during the Landslide mitigation preliminary design stage.

The design of stabilization or protective works may be beyond the scope of the Landslide Assessment and may be considered a specialty engineering service. Ideally, conceptual designs should be submitted to the Local Government for approval in principle, before time and effort is expended on detailed designs. Stabilization or protective works must not transfer Landslide Hazards and/or Landslide Risks to other properties.

Stabilization or protective works that are constructed to reduce Landslide Hazards and/or Landslide Risks on multiple properties may require ongoing operation and maintenance that will often have to be approved by the Local Government and/or provincial government, possibly including the provincial Inspector of Dikes. In addition, the Local Government and/or provincial government may require permanent access to such works. Such consultations are essential, as failure to discuss the proposed works with the Approving Authorities may lead to their rejection at the sign-off stage.

H.3 SELECTING THE DESIGN EVENT

A design event can be defined as the Landslide scenario(s) to which the risk-reduction or hazard-reduction measures are scaled and ultimately constructed. Historically and currently, a design event is linked to a specific return period; for example, a 200-year or 500-year return period.

In some cases, the event trigger is not natural (for example, intentional or unintentional drainage redirection, poor fill placement, broken water lines, blocked culverts). This implies that the background (undisturbed) Landslide frequency is changed until such time as the cause has been remedied. In those instances, the principle of return period does not apply, and it is more appropriate to refer to an encounter probability (such as a 10% chance of occurrence in the next 50 years). The decision of the encounter probability in those cases will largely be judgment based.

The QP's decisions based on professional judgment must be supported with the appropriate field observations, as well as examinations of document case studies of similar conditions

The design event must be carefully justified. For flood mitigation works, the 200-year design standard is embedded in provincial legislation (BC WLAP 2004); however, this is not the case for Landslides. Currently, there is no such guidance for Landslides. In jurisdictions that have adopted hazard-based life-safety criteria, the design event would be the adopted hazard level.

In the case of a quantitative risk assessment, the appropriate design event, however, can be chosen by evaluating different return-period scenarios against the life-safety or economic benefits afforded by the mitigation structure. The design event selected would achieve the required life-safety or economic threshold at an optimized cost-benefit ratio.

The reasoning for the definition of a design event needs to be well argued in collaboration with the Approving Authority and the Client. It should not be a haphazard decision, and the residual hazard should be characterized. This can be accomplished by showing the effect of the hazard-reduction structure on the hazard maps, which will allow Landowners to understand the effects of the structure. These steps are essential, to avoid the possible misconception that the structure or mitigation components will provide total safety from Landslide events.

H.4 DETERMINING AND IMPLEMENTING RISK-REDUCTION MEASURES

H.4.1 EVALUATING RISK

A nuanced approach to risk evaluation should be considered in British Columbia (BC). The following key points support decision-making when assessing risk:

- Interpretation of the condition of the structures and their ability to withstand future loading (i.e., vulnerability).
  - For example, a debris-flow net, which, once filled, will lose storage capacity or deteriorate over time.
- Confidence in the risk estimates and weighing whether additional information is likely to change the need to take risk action, and defending the decision if the estimated risk justifies mitigative action.
  - For example, if the initial hazard assessment was conducted on a low budget, and thus the resulting risk estimates have a low confidence, it may be prudent to upgrade the hazard study to test if mitigation is actually necessary and to lower the uncertainties associated with the mitigation measure design.

- – Every step in the risk evaluation process must be clearly described, fully transparent, and consistent, to make the assessment defensible.
- The urgency of the risk-reduction measures.
  - – For example, considering whether the Landslide is imminent (e.g., evidence of measured acceleration, open tension cracks, obvious bulging, recent signs of distressed vegetation), or whether it is dormant or inactive. Or, where there is evidence of recent watershed changes (e.g., wildfire, poor road construction, mine waste-rock placement), considering whether that may worsen an existing situation.
  - – This would be in contrast to a Landslide type that has a lower annual probability of occurrence, and hence a lower chance of occurrence in the immediate future.
- Recommended actions that are coherent and make sense.
  - – Many mitigation systems need to be conceived and function in series (called a "functional chain" in Austria and elsewhere). An example is a debris-flow breaker and downstream retention structure, followed by erosion-control measures and grade-control structures on the fan reaches, such as deflection berms.
  - – Each system component must be designed to acknowledge upstream and downstream structures and the geomorphic processes being changed by such structures. This is not the case, for example, for a simple rock-fall structure (berm or net) where a non-functional chain is required.

The general guidance on locations for which Landslide mitigation is prioritized is as follows. In cases where failure is imminent and life loss possible, the highest priority would automatically apply:

- Cases where both Landslide failure probability and annualized life loss are high versus cases where only either of the two is high. However, equal weight would be placed on cases where one or the other (life loss or failure probability) exceeds the guidance thresholds.
- Situations where high life loss or failure probability is dominated by a single failure mode, rather than where several failure modes must interact to result in a high risk.
- Cases where the uncertainty bounds are tight, and mean and median estimates are close to each other, compared to cases with significant data scatter, and mean and median risk estimates lie far apart.
- Locations where mitigation is technically easy and inexpensive versus where mitigation is difficult and expensive.

H.4.2 STRUCTURAL (ACTIVE) AND NON-STRUCTURAL (PASSIVE) RISK-REDUCTION MEASURES

It is important to differentiate between structural and non-structural mitigation measures. In these guidelines, the terms "structural" and "non-structural" are equivalent to the terms "active" and "passive," respectively.

Structural, or active, measures are not defined as those requiring a structural engineer, but rather those that meet the following definition of the United Nations Office for Disaster Risk Reduction (UNDRR):

> "Structural measures are any physical construction to reduce or avoid possible impacts of hazards, or the application of engineering techniques or technology to achieve hazard resistance and resilience in structures or systems." (UNDRR 2021)

The UNDRR also defines non-structural mitigations as follows:

> "Non-structural measures are measures not involving physical construction which use knowledge, practice or agreement to reduce disaster risks and impacts, in particular through policies and laws, public awareness raising, training and education." (UNDRR 2021)

Non-structural, or passive, measures can be viewed from an objective-oriented perspective similar to that used for structural measures. Landslides are associated with high Consequences due to the presence of Elements at Risk, and the vulnerability of those elements. Therefore, the purpose of passive mitigation techniques is to permanently, or temporarily, relocate people and infrastructure, or to improve the resilience of people and infrastructure to Landslides.

H.4.3 PUBLIC EDUCATION

It is vital to provide the public with information on the results of hazard and risk studies in which the uncertainties are explained in language that can be understood by non-professionals.

Public meetings should also be held in which the QP and representatives of the provincial government or the Local Approving Authority are available to answer questions. Information can also be provided in these meetings about how the public can individually reduce their own risk; for example, by knowing which parts of a building are the least vulnerable or how a building can be made more resilient to Landslide impact.

H.4.4 MONITORING, WARNING SYSTEMS, AND EVACUATIONS

The purpose of monitoring and warning systems, along with the emergency response plan, is to notify individuals at risk in the event of a potentially catastrophic Landslide, allowing them time to evacuate to a safe location. Individuals at risk are people located within the potential impact zone.

It is important to note that certain hazard types or situations may not be amenable to monitoring, warning, and emergency response.

- Monitoring systems:
  - Monitoring provides awareness and information in advance of imminent failure or failure occurrence, usually based on regular, relatively simple, and inexpensive field surveys or through remote sensing techniques at various levels of sophistication.
- Warning systems:
  - If an alert notification must be issued, the warning systems and emergency response plan will allow key groups of individuals to respond in an organized manner, according to a protocol developed in advance for different alert levels.
  - For new developments, warning systems should not be considered a viable risk-reduction measure because they cannot prevent economic damages, and there is no guarantee that all residents will be successfully evacuated even if the monitoring and warning systems perform as designed.
  - For existing developments, where it is determined that active (structural) or passive (non-structural) mitigation measures are not feasible, or prior to the implementation of mitigation measures, monitoring and warning systems and an emergency response plan can be designed and implemented, but these emergency measures may only be relied on to manage risk to the level of certainty afforded by the applied technologies and systems.
- Emergency response plan:
  - The emergency response plan should be developed in combination with the monitoring and warning systems.
  - This measure requires maintaining public awareness of the plan, particularly regarding evacuation. As various studies worldwide have shown (e.g., Jonkman and Vrijling 2008), not all residents are willing to evacuate, and some fatalities are still possible.

- An emergency response plan may involve increasing the frequency of monitoring and adding monitoring methods; preparing protocols, contracts, materials, and equipment needed for emergency response; and developing communication protocols and evacuation protocols.
- Training and drills should be considered part of the emergency response plan. An example of a monitoring, warning, and response plan developed for Turtle Mountain in Alberta is detailed in Froese and Moreno (2014).

The cost of a monitoring, warning, and emergency response plan ranges from several tens of thousands to hundreds of thousands of dollars. Some monitoring instruments may need to be replaced at times due to weather damage, animal damage, or vandalism.

A key aspect of any monitoring and real-time warning system is the ownership of the system, and thus the responsibility for maintaining it. This also includes quality control, system reliability, data management, and public interfacing. This has not been clarified in BC and should be negotiated on a case-by-case basis. Unless a long-term funding source is guaranteed, these programs may end, which may mean that warning systems may be discontinued. These considerations need to be discussed with Approving Authorities and Local Governments issuing a Landslide Hazard or Landslide Risk assessment.

H.4.5 LAND-USE ZONING

The purpose of land-use zoning is to minimize exposure of both individuals and infrastructure to a Landslide, and to position key infrastructure such as Residential Developments, municipal government buildings, roads, and oil and gas pipelines and other industrial facilities at zones where the risk is tolerable or broadly acceptable.

Land-use zoning should be based on Landslide Hazard and Landslide Risk assessments. Such policy may include zones where hazard or risk is either not apparent or is low or acceptable; where it is moderate and may require detailed assessment; and where it is high and unacceptable for new development.

Figure H - 1 below provides an example of a hazard map based on the combined probability of the hazard and impact forces. Such a map, especially if created prior to a development, can be translated into a land-use map in which each zone is attributed with specific caveats ranging from “no development in absence of comprehensive site-wide mitigation” to “development possible without restrictions” (see Appendix F: Evolving Practice, subsection F.8 Landslide Hazard Mapping).

Zoning and land-use controls are important tools. QPs considering using these approaches should work closely with the Local Government to identify an approach that is consistent with Local Government powers and uses the right tools (e.g., community plans, zoning, development permit areas).

QPs should also recognize that land-use zoning can be a complex undertaking and requires specialized knowledge of land use regulation.

H.4.6 PHYSICAL RISK-REDUCTION MEASURES

The selection of risk-reduction measures, loading determination, and Landslide mitigation design is the responsibility of the QP. Through literature review and field observation, QPs need to acquire the specific information necessary to be able to determine the appropriate risk-reduction measures; to define and calculate corresponding loading scenarios; and to design mitigation works. Engineering designs require calculations to be checked independently (see Section 4.1.5 Documented Checks of Engineering and Geoscience Work).

Professional judgment grows with experience and repeated observations, especially of physical protection measures that failed. Furthermore, much knowledge is not transferable from one process to another. For example, a riprap groin that is suitable for bank erosion protection in a gravel-bed river is unlikely to work as a mitigation structure on a creek subject to debris flows, as large boulders several metres in size can be entrained in a debris flow due to the higher fluid density, induced buoyancy, and shear stresses. Similarly, measures to prevent fragmental rockfall (e.g., nets, bolts, and anchors) may be inadequate for deeper-seated rockslides. Thus, it is the QP's responsibility to fully understand the failure mechanisms and reconcile those with the proposed mitigation design. Implemented mitigation designs must not become part of the problem by becoming part of the Landslide itself (or by redirecting the hazard to other onsite or offsite sensitive receptors), hence leading to downslope risk transfer.

Physical mitigation measures can be further refined based on their function (Hübl et al. 2005; Carladous et al. 2016). Landslides are hazardous processes due to a variety of characteristics, including high velocities, discharges, rates of deformation or impact forces, high erosion-transport and high sediment-transport potential, and depth of burial. The risk of the overall event can be limited by altering one or more of these characteristics; e.g., by velocity reduction, spatial impact lowering, or erosion prevention. The risk can be further controlled by addressing several or all of the characteristics potentially leading to loss. International experience suggests that use of a single mitigation technique is often insufficient, because of the lack of redundancy. Instead, measures are combined to create a "functional chain" of mitigation (Kettl 1984; Fiebiger 2008). The utility of this chain is improved by including a range of mitigation techniques, which serve different objectives with respect to Landslide Risk control (Moase 2018).

It is primarily the responsibility of the QP to determine appropriate physical risk-reduction measures. Usually, it is recommended that an option analysis be carried out that first identifies mitigation options; then reduces the options to those that are most viable and cost-efficient; and then scores and ranks the remaining options according to topic, such as life-loss and economic risk reduction, technical feasibility, permitting requirements, and ecological and social impacts. This will promote fair and transparent use of available funds.

Such option analyses should be carried out in close collaboration with the Approving Authority, especially in cases where the Local Government will ultimately own the structure and be responsible for its maintenance and operations costs. This collaboration is crucial, particularly for design elements that regularly retain debris and thus require annual budgets for debris removal. For Local Governments with low tax income, the costs associated with removing thousands of cubic meters of debris may not be affordable, and other funding mechanisms may have to be sought (e.g., local area taxation for the development to be protected, arrangements with the provincial government, or insurance).

Where such works will be owned and maintained by private Landowners, an operations and maintenance plan must be provided to the local Approving Authority, together with a registered Covenant on the property title. QPs need to be prepared for field reviews and post-Construction inspections that are reported to the Approving Authority to demonstrate that the works were built as designed.

After significant Landslides, inspections must be conducted, and the Approving Authority informed, to assure that the works are still operable and able to withstand the design event.

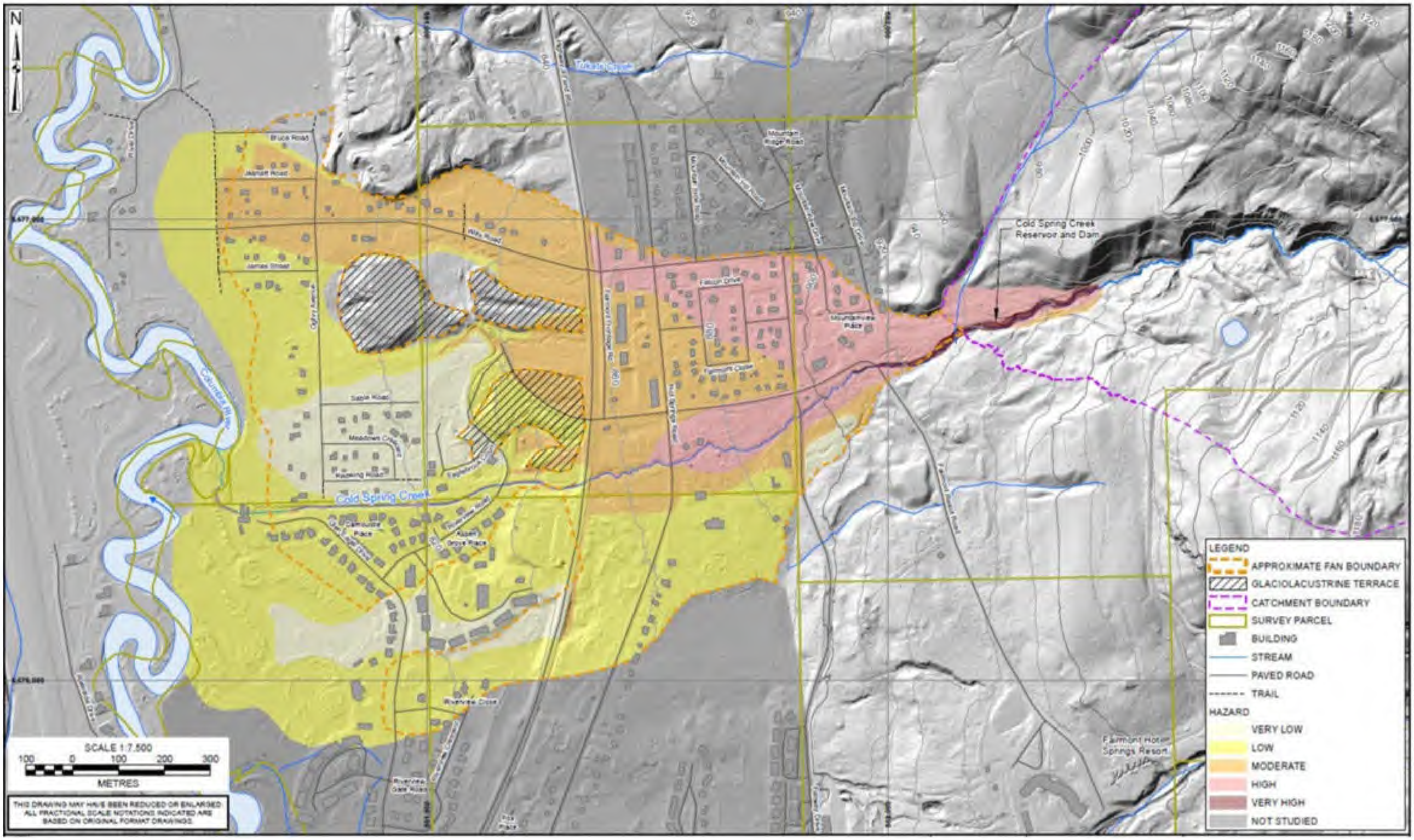

Figure H - 1: Example of a composite hazard map showing different hazard zones defined by impact force x frequency

NOTES:

Map of Cold Springs Creek, Regional District of East Kootenays (RDEK) (BGC 2020). Reproduced with permission from RDEK.

H.5 REFERENCES – APPENDIX H

The following documents are referenced in Appendix H of these guidelines:

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APPENDIX I: AUTHORS AND REVIEWERS

The following are the authors and reviewers of the 2022 revision of these guidelines. All contributors are presented in alphabetical order by last name within their respective sections.

AUTHORS

Pierre Friele, MSc P.Geo., P.L.Eng.

Matthias Jakob, PhD P.Geo., P.L.Eng.

Dan Rankin, P.Eng.

James Wetherill, P.Eng.

REVIEWERS

Scott Cosman, P.Eng.

Graham Daneluz

Fiona Dercole

David Gerraghty, P.Eng.

Gordon Hunter, MSc P.Eng.

Scott McDougall, PhD P.Eng.

Eric McQuarrie, P.Eng., P.Geo.

Tom Millard, MSc P.Geo.

Tim Smith, MSc P.Geo., P.L.Eng.

Calvin VanBuskirk, P.Eng., P.Geo. FEC, FGC

Guoxi Wu, PhD P.Eng.

NOTES:

200 • 4010 REGENT STREET, BURNABY, BRITISH COLUMBIA, CANADA V5C 6N2
MAIN 604.430.8035 TOLL FREE 1.888.430.8035 EMAIL info@egbc.ca WEBSITE egbc.ca