According to Ken Ho (pers. comm. 2016), Deputy Head of the Hong Kong GEO. landslide QRAs have been applied in two areas:

- Overall or portfolio QRAs to assess a given group or category of slopes (man-made or natural) in assessing the scale of problem (overall risk), risk distribution and risk profile, together with evaluating the cost effectiveness of a landslide mitigation program, mainly to provide a basis for formulating slope safety strategy and setting slope safety policies.
- Site specific QRAs, which are mainly applied to natural slopes in order to evaluate the level of risk and the risk tolerability, and to develop the necessary risk mitigation measures.

The former has proven to be useful in Hong Kong. The latter has been applied only sparingly to selected sites with circumstances that warrant its use, apparently due to resource limitations. For man-made slopes, the conventional approach of using factors of safety calibrated against experience are viewed to be sufficient whilst for natural terrain, a design event approach (DEA) which is equivalent to a hazard-based approach is generally preferred to QRA.

For site specific QRAs, GEO endeavors to consider the full range of credible landslide events (as characterized by the nature, volume and mobility) in principle. The corresponding return periods for this purpose have not been codified, but in general landslide scenarios with return periods typically up to 1,000 years for natural terrain landslides are considered. In fact, GEO (2014) states "*The design event is a sufficiently realistic estimate of the credible failure volume (e.g. based on recent landslides as well as relict landslides with a high degree of certainty) that may be encountered during the design life of the affected facilities. A 'Conservative Event', as referred to in the First Edition of GEO Report No. 138 is intended as a less severe design event than a 'Worst Credible Event' for hazard mitigation for circumstances with a lesser risk concern, with a notional return period in the order of 100 years".* To account for effects of climate change, landslides with a return period in the range of >1,000 years and up to about 10,000 years have been examined as a "sensitivity check" (Ho, pers. comm. 2016). The 10,000-year return period, however, has not yet been implemented in policy. This was only done in the overall QRA (see above), and not in site-specific QRAs or for the design event approach.

B.1.2. Australia

A framework for landslide risk management was released by the Australian Geomechanics Society (AGS) in 2007 that closely follows the QRA guidance by Hong Kong's GEO. However, the AGS framework does not specify levels of tolerable or acceptable risk; rather, they place the onus on the client/owner/regulator to decide the risk tolerance thresholds. When levels of tolerable and acceptable risk have been set, estimated risks are compared to those thresholds in order to assess and prioritize options for risk management.

B.1.3. New Zealand

The Resource Management Act in New Zealand delegates the selection of risk tolerance criteria to local governments (Enright 2015). The City of Christchurch has also adopted the individual risk tolerance criteria adopted by Hong Kong (1:10,000 for existing construction and 1:100,000 for new construction).

B.1.4. Switzerland

The Swiss Federal Government has adopted a landslide hazard mapping program for land-use planning. The Swiss framework defines very low, low, moderate and high hazard on the basis of the probability of occurrence and the intensity i.e., depth and velocity, of the landslide. The probability ranges are defined as 1 to 30 years, 30 to 100 years, 100 to 300 years and greater than 300 years, though the latter class has not upper-class boundary. This compares to a 150-year return period hazard-based approach in Austria (Huebel, pers. comm. 2015). Swiss hazard probability tolerance zones have limited legality unless they are approved by the local council and incorporated into local land-use management plans. Any change to a local plan must also be vetted by cantons (Hungr et al. 2016).

The Swiss Platform for Natural Hazards (PLANAT 2014) gives a tolerable risk criteria of "The annual risk of being killed as a result of natural hazards is significantly lower than the average probability of death for the age group with the lowest mortality rate in Switzerland." A previous version of PLANAT, released in 2009, proposed an individual landslide risk goal of 1:100,000 for residential areas; however, the approach of adopting a specific individual risk number has not yet been carried forward (Hungr et al., unpublished).

B.1.5. European Union

Landslide hazard and risk assessment practices in the European Union were documented by Corominas et al. (2010) as part of the European Commission's SafeLand project. Some recommendations for practitioners carrying out quantitative risk analyses were subsequently provided by Corominas et al. (2013).

Although a few references were made by Corominas et al. (2010) to landslide return period ranges that have been considered in Italy, France and Andorra, which are similar to those discussed for Switzerland above, no references were made to landslide risk tolerance thresholds. Corominas et al. (2010) state that "*The establishment of common tolerable and acceptable threshold values for the whole of Europe remains an open point for discussion*".

B.2. DEVELOPMENT OF STANDARDS IN CANADA

There is currently no nationally adopted level of landslide safety in Canada. The majority of risk management strategies are decided upon by councils of the respective municipality, summarized in Table B-1.

In BC, assessments of slope stability and potential slope movements under seismic loading are based on the 2,475-year return period earthquake ground motions (APEGBC 2010), consistent with guidance provided on the seismic design of structures in the BC Building Code and the National Building Code of Canada. However, in terms of public safety, practitioners in BC are required to state that "the land may be used safely for the use intended", as noted in the Land

Title Act (Section 86) and the Community Charter (Section 56). The key problem with this wording is that it triggers the questions: “What is safe?” and “How safe is safe enough?”. Specifically, practitioners should not be expected to decide on society’s risk tolerance thresholds as this could lead to widely differing standards from project to project. Instead, and as shown by jurisdictions elsewhere, a national or at least a provincial standard should be created without which risk assessments are incomplete.

Return periods still play an important role, as a range of return period need to be considered in both hazard-based and risk-based approaches. For example, MoTI (2009) advises to use a 10,000 year return period for life-threatening landslides. The use of the 10,000-year return period event has recently been reviewed and discussed by Jakob et al. (2018).

In that, BC’s return period guidance is the most conservative worldwide compared to Austria (design return period of 150 years), Switzerland (design return period of 300 years with some estimate of residual risk associated with return periods greater than 300 years) and Hong Kong (100 to 1,000-year return period).

Table B-1. Summary of landslide hazard and risk management strategies in Canada (Porter and Morgenstern 2013; Hungr et al., unpublished).

Jurisdiction/Organization - Location	Dates	Landslide Risk or Hazard Management Strategy
City of Ottawa	2004	Defines “hazard lands” as slopes with FS < 1.5 or seismic FS < 1.1 Development is typically precluded within hazard lands, allowances provided for flow slide retrogression and erosion where appropriate.
Canadian Geotechnical Society – Canada-wide	2006	Recommends considering the possibility of landslides, greater factors of safety should be used for higher consequence and/or uncertainty situations. There is no specific discussion on risk.
City of Calgary	2009	Geotechnical report required for all sites with slopes exceeding 15% or where the City Engineer determines there is a concern. Minimum FS = 1.5 for all development, setback limits for developments based on FS = 1.5
Town of Canmore, Alberta	2013 to present	Unacceptable debris flood risk mitigated to ALARP level and less than 1/10,000 PDI by constructing debris flood risk reduction measures for sites that have received funding through the Alberta Community Resiliency Program.

Jurisdiction/Organization - Location	Dates	Landslide Risk or Hazard Management Strategy
Alberta Environment and Parks – Alberta-wide	2015	No specific risk to life or economic risk criteria, stakeholders advised to agree on tolerable safety risk at beginning of a study (see AEP 2015)
Fraser Valley Regional District	2017	Dictates hazard-related responses to development approval applications based on annual return frequencies.

Landslides risks in BC have been managed in a variety of forms that are summarized in Table B-2.

Table B-2. Summary of landslide hazard and risk management strategies in BC (APEGBC 2010, Hungr et al. unpublished and supplemented with BGC data).

Jurisdiction/Government-Location	Dates	Adopted Hazard or Risk Levels
BC Supreme Court – Squamish-Whistler Corridor	1973	Set precedent for the level of landslide safety for residential development at P(H) = 1/10,000 of a major landslide.
MoT – Province-wide	1978 – 1993	Recommended P(H) = 1/475 for proposed subdivisions (orienting on the National Building Code standards).
Regional District of Fraser-Fort George	1999	Level of landslide safety, P(H) = 1/475
District of North Vancouver Council	2005	Adopted Hong Kong standards as an interim guideline for PDI.
MoTI – Highway 16 near Legate Creek	2008	Quantification of landslide risk to vehicles crossing the fan of Unnamed creek. Mitigation measures implemented to reduce risk to the travelling public.
MoTI – Province-wide	2009	Levels of landslide safety defined as: • P(H) = 1/475 of a damaging landslide at a building site • P(H) = 1/10,000 of a life-threatening or catastrophic landslide • Large scale developments must also consider total risk and international standards.
District of North Vancouver Council	2009	ALARP level of landslide safety for group risk plus:

Jurisdiction/Government-Location	Dates	Adopted Hazard or Risk Levels
		PDI[1] Risk = 1/10,000 of a fatality for a building permit for < 25% increase in gross floor area, otherwise PDI Risk = 1/100,000 of a fatality. Alternatively risk is mitigated with target static and non-static factors of safety. Note that the PDI risk levels have been adopted as bylaw by council. The group risk criteria have been adopted on an interim basis.
Squamish Lillooet Regional District	2015	Informal adoption of Hong Kong life loss risk tolerance criteria for PDI and Group risk for landslide risk for Catiline Creek only. • PDI Risk: 1/10,000 for existing development • PDI Risk: 1/100,000 for new development • ALARP zone for Group Risk.
District of Squamish	2015	Hong Kong life loss risk tolerance criteria for PDI and Group risk adopted for landslide risk across the district. • PDI Risk: 1/10,000 for existing development • PDI Risk: 1/100,000 for new development • ALARP zone for Group Risk Adopted by council resolution.

[1] PDI stands for “probability of death of an individual”.

APPENDIX C
CONCEPTUAL MITIGATIONS

C.1. INTRODUCTION

If the risk assessment identifies an unacceptable risk, mitigation can be used to reduce the risk to a tolerable level. Mitigation involves reducing either the magnitude, intensity, or probability of the hazard, or the severity of the consequences. There are two categories of mitigation techniques:

- Structural measures involving the construction of barriers, dikes, or slope stabilization
- Non-structural measures involving temporary or permanent removal of elements at risk from hazardous areas or changing people's behavior to reduce vulnerability.

C.1.1. Structural Mitigation Conceptual Design

The objective of the conceptual design phase is to identify and develop feasible mitigation design options. Identification of feasible structural mitigation measures primarily depends on the accessibility of the watershed, channel and fan apex, and the level and type of development on the fan. It is also important to consider the types of processes that contribute to the hazard, such as side-slope landslides or channel erosion.

Once feasible mitigation options have been identified, the options are developed and sometimes combined into conceptual systems or "functional chains" that meet the design basis established during project scoping. A mitigation system can be a set of structural and non-structural measures that interact to provide redundancy and meet hazard or risk reduction targets. The mitigation systems consider factors including:

- Measures requiring minimal maintenance or intervention are likely to perform better and cost less in the long run, but sometimes can cost more to construct
- Measures that avoid disrupting the normal streamflow are generally preferable from an environmental and regulatory perspective
- If the sediment load is removed from a high discharge flow by a regulation or retention structure, the flow will tend to scour and entrain debris downstream of the structure, unless the channel is sufficiently protected.

The conceptual design process typically identifies several feasible system options for comparison.

Figure C-1 shows selected examples of structural mitigation measures. These measures are often combined to create a "functional chain" of mitigation. The most effective mitigation systems include a range of different techniques, to provide redundancy and optimize risk reduction.

Figure C-1. Examples of debris-flow mitigation structures: (a) an earth-fill retention berm on Glyssibach, Brienz, Switzerland; (b) a stone diversion berm, Trachtbach, Brienz, Switzerland; (c) a conveyance channel with earthfill berms, Rennebach, Austria; (d) log crib check dams, Gesäuse, Austria; and (e) a flexible debris net for debris flood mitigation, Cougar Creek, Canmore, Alberta. Photograph (d) by M. Jakob, other photographs by E. Moase.

C.1.2. Non-Structural Measures

Non-structural measures for flooding and slope risk management typically include the following options:

- **Education** – Provide training for residents and workers who are commonly exposed to hazards. Training topics include: how to interpret hazard maps and identify areas exposed to hazards; causes and triggers of events; measures that individual property owners can take to protect themselves; emergency preparedness; and actions to take during an event. This can reduce the vulnerability of individuals to hazardous events.
- **Emergency Management Planning** – Develop plans to respond during or immediately after an event. This would typically involve plans for evacuation, checking in with neighbors, and staging of equipment and materials. This can reduce the consequences of a hazard event and improve resilience of the community.
- **Relocation** – Remove buildings from hazard zones. This can eliminate safety and economic risk from hazard sources, but the costs and tradeoffs can be prohibitive.
- **Temporary Evacuation** – This can include precautionary evacuation from hazard zones during periods of heavy rainfall, or alarm systems that signal an event has started. An alarm would provide only seconds or minutes of advance notice for the processes affecting Zeballos. This method can reduce safety risk but does not reduce property damage. This method can be difficult to implement effectively because of large uncertainties in predicting events, the possibility of frequent false alarms, and the requirement for occupants to evacuate quickly and without assistance.
- **Development Restrictions** – This involves creation of zones where future development is not allowed. This should be based on hazard maps that are updated as conditions and topography change. Particularly, construction of structural mitigation measures can change the debris flow and debris flood impact location and extents.

Selection of appropriate mitigation depends on several factors, including the process type, current and future land-use, and budget. The following section explains the approach that BGC uses to select and develop debris-flow and debris-flood mitigation designs.

C.2. POTENTIAL MITIGATIONS

Locations exposed to “High” slope risks can be mitigated by a combination of measures. Table C-1 is a list of conceptual mitigations with BGC’s assessment of the effectiveness and practicality.

Table C-1. Conceptual slope hazard mitigations.

Mitigation	Description	Debris Flow	Rock Fall	Rock Slide
Stabilize source zone	Remove or stabilize unstable rocks/debris	-	-	-
Stabilize creek bed	Reduce erodible material in creeks	✓	-	-
Consolidate creek	Elevate creek bed to stabilize side slopes	✓	-	-
Debris retention	Permanent or temporary debris storage	✓	✓	-
Debris regulation	Temporarily storing debris	✓	-	-
Energy dissipation	Decrease size or velocity of flow	✓	✓	-
Diversion	Redirect flow away from Village	-	-	-
Improve conveyance	Improve a defined travel path to guide debris to a desirable location	✓	-	-
Protect buildings/infrastructure	Use of damage-resistant construction methods	✓	✓	-
Relocation	Permanent or temporary relocation of people and infrastructure	✓	✓	✓
Emergency preparedness	Protocols to manage and limit risks if a disaster occurs	✓	✓✓	✓✓

Notes:

Mitigations marked with - are expected to be ineffective.

Mitigations marked with ✓ are considered potentially effective but impractical.

Mitigations marked with ✓✓ are considered potentially effective and practical.

Potential mitigations could include:

- **Education and rain fall warning system –** Slope hazards are most commonly triggered by periods of intense rainfall and earthquakes. The Village could implement a system of alerting and evacuating residents when a pre-determined rainfall intensity is reached, or an earthquake of a pre-determined magnitude is reported. Much like a tsunami warning system, the alerts would require automation and enforcement by local officials. Hazard awareness education could involve information flyers that are mailed to homeowners, as well as public meetings.

- **Debris basins to contain avulsion potential –** The majority of the debris flow risk comes from avulsion scenarios in which flows spill out of the existing channel and impact a portion of the fan away from the existing channel. Improving the channel would require extensive earthworks and, by comparison, installing basins on the fan could be a cost-effective option for managing risk. Potential locations are vacant lot 116 in the former school location and vacant lots between lots 208 and 214. Basins would require an outlet structure and ditching/culverts to direct flow toward the river.
- **Relocation –** The area delineated on Drawing 2, is subject to rock fall, rock slides and debris flows. The August 2018 wildfire has worsened the hazards and thus risks. Should structural mitigation not be feasible (i.e., too expensive), and should the Village decide that risk to certain properties remains intolerably high, relocation of some properties may be an appropriate response. This has already occurred with the old high school which is now located in west Zeballos. High-lying terrain exists within the Village and adjacent areas and BGC could provide guidance on the geotechnical suitability of such sites.
- **Monitoring –** Monitoring slope deformations can provide advanced warning of impending rock falls, rock slides, and debris flows. Thick vegetation limits the usefulness of most remote sensing techniques and the best tool may be periodic visual inspections by a qualified geohazard professional. With repeated inspections the forest regeneration can be tracked and the hazard likelihood updated. When paired with communication and evacuation protocols such an early warning system would provide an alert to the community when the rock slope movement is accelerating and likely to detach from the slope and become a slope hazard.

Table C-2 provides a comparison of the identified slope hazard mitigation options.

Table C-2. Comparison of slope hazard mitigation options.

Criteria	Warning System	Debris Basin	Relocation	Monitoring
Cost*	Low to moderate - Depends on the scale of the work	High – would require detailed engineering design and construction quality assurance	High – would require Provincial/Federal assistance	Moderate – Depends on frequency of inspections
Risk reduction	Depends on the resident, including degree of advance preparation and long-term memory about the recommendations	Would reduce flow intensity, even if broken or damaged in the event; design should consider potential risk transfer caused by flow diversion	Would remove elements at risk from high intensity hazard zones	Depends on inspection frequency. Inspections could provide advanced warning on large scale events but would likely not for rapidly initiating slope hazards.
Impact to residents	Success of the measure depends on resident involvement	Moderate – land use changes to vacant land may impact residents	High – depends on land availability	Low – success of the measure depends on resident's willingness to evacuate if a hazard is identified

* Cost comparison categories are approximate, as follows: Low means <$10,000; Moderate means $10,000 - $100,000 and High means >$100,000.

DRAWINGS