Proposed Landslide Risk Tolerance Criteria

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ABSTRACT
For residential development to proceed on ground potentially exposed to a landslide hazard in British Columbia approving authorities require a letter from a professional engineer or geoscientist stating that the site is safe for the intended use. Safe, however, is nowhere defined and there is no consistent guidance on this matter. APEGBC (2008) discourages its members from making such statements in their reports unless "safe" is explicitly defined. This paper reviews the development and application of the landslide risk tolerance criteria used in North Vancouver and compares the criteria with risks faced by Canadians in everyday life. Landslide scenarios most amenable to a quantitative risk-based management approach are distinguished from scenarios where "safe" sites might be more appropriately defined by a factor of safety or hazard probability.

RÉSUMÉ
En Colombie britannique, avant tout développement résidentiel dans une zone potentiellement exposée à des glissements de terrain, la loi exige la remise d'une attestation de la part d'un ingénieur professionnel ou d'un géoscientifique, stipulant que le site est sans risque pour l'utilisation qui doit en être faite. Cependant, ce que l'on entend par sureté d'un site n'est pas précisé pas plus que ne sont rédigées des directives cohérentes sur la question. APEGBC (2008) déconseille à ses membres de délivrer de telles attestations tant que le terme « sureté » n'est pas explicitement défini. Cet article passe en revue le développement et l'application de critères de tolérance au risque de glissement de terrain mis en œuvre au nord de Vancouver et évalue la pertinence de ces critères au regard des risques auxquels les Canadiens sont quotidiennement confrontés. Les scénarios de glissement de terrain les plus enclins à une approche quantitative de la gestion des risques sont distingués des scénarios où la « sureté » des sites pourrait être définie de façon plus appropriée par un facteur de sécurité ou la période de retour de l'aléa.

1 INTRODUCTION

In British Columbia landslides kill approximately 3 people per year and cause an estimated $2.5 to $3.5 million in direct damages to residential development (Hungr 2004). While the average resident's risk of loss of life is low (approximately 1 in 1,000,000 per annum), the statistics are significantly influenced by the much higher risk faced by a relatively small percentage of the population. It is the responsibility of approving authorities, developers, and qualified professionals to manage these risks in a practical way that balances cost and benefit.

According to Association of Professional Engineers and Geoscientists of British Columbia (APEGBC 2008) practice guidelines a landslide "safety" assessment for residential development comprises two principal steps: estimation of the level of hazard or risk, and comparison of the result against acceptance criteria. If the acceptance criteria are met, the site may be deemed "safe for the use intended." Otherwise, means of reducing the hazard or risk to acceptable levels must be prescribed before development is considered further.

Within British Columbia landslide acceptance criteria are most commonly based upon factors of safety, hazard probability, or, more recently, risk of loss of life. Some methods of assessment are better suited to certain landslide types and development scenarios than others. Unfortunately, province-wide acceptance criteria do not exist and it is often left up to the qualified professional conducting the safety assessment to determine which method to use and the acceptance criteria values. This has several significant shortcomings. The minimum level of landslide safety can be expected to vary between municipalities and regional districts, and even between adjacent properties in jurisdictions where such guidance is lacking. Furthermore, qualified professionals conducting these assessments take on unwarranted liability by prescribing a level of landslide risk tolerance, which is a societal issue that should be determined by government as is the case, for example, in Hong Kong, Australia, Switzerland and Austria.

Following a fatal landslide in 2005, the District of North Vancouver adopted, on an interim basis, quantitative risk tolerance criteria to help manage safety where existing developments are potentially subject to debris slides and debris flows. Similar criteria for proposed new developments are being considered by the municipality. A Coroner's report on the landslide fatality further recommended that Provincial landslide safety criteria be established, which is timely since the authors are aware of at least four additional studies in British Columbia where quantitative risk tolerance criteria are being used to determine if risks are acceptable and to define appropriate risk reduction measures.

While it is not the role of the engineer or geoscientist to prescribe an acceptable level of public safety, our professions are in a position to help decision makers better understand the advantages and limitations of the different methods of assessment, how hazard and risk acceptance criteria have been used elsewhere, and some of the technical and economic implications if certain acceptance criteria were to be adopted at a provincial or federal level. This paper attempts to shed light on some of these issues, with particular emphasis on risk of loss of life as a measure of landslide safety.

2 ACCEPTANCE CRITERIA OPTIONS

Landslide safety acceptance criteria should form the technical basis for approval of new development and for determining if hazard or risk at existing development is tolerable. The criteria should account for both the potential for economic loss and loss of life, and regardless of the assessment methodology, the respective acceptance criteria should result in approximately the same level of safety. In addition to prescribing a minimum level of safety, approving authorities require systems to ensure that target safety levels are met through the design and construction process, and that landslide risk does not increase over time as a result of slope modification, changes in the upstream watershed, failure of drainage systems, and other factors that cannot always be controlled or forecast at the time of development.

Three types of landslide safety acceptance criteria are discussed below.

2.1 Factor of Safety Approach

In a limit equilibrium slope stability analysis, the factor of safety represents the ratio of forces resisting failure to those promoting failure. Factors of safety are used in engineering design to account for uncertainty in the input parameters (soil or rock strength, groundwater conditions, external loads), limitations of the calculation methods, and to avoid small strains that may lead to loss of soil or rock strength and progressive failure. Implicitly, the selection of a factor of safety is a risk-based decision.

It is common engineering practice to use factors of safety equal to or even greater than 1.5 for permanent slopes under static conditions and greater than 1.0 under seismic design loads provided deformations are acceptable. APEGBC (2008) guidelines provide methods to predict the displacement of slopes under seismic loading using factor of safety calculations and recommend that predicted displacement of slopes upon which residential development will be founded not exceed 15 cm during the design earthquake.

There are several instances in British Columbia where development has occurred on large pre-existing landslides that were not detected during the approval and development process. In some of these cases a factor of safety approach might be used to assess the relative improvement in stability achievable through various stabilization options. Compared to first-time failures, pre-existing landslides offer greater opportunity to reduce model and parameter uncertainty through geotechnical investigation, monitoring, and slope stability back analysis, and there may be justification in adopting a lower factor of safety under these circumstances.

Probabilistic slope stability analyses offer a means of assessing the effects of parameter uncertainty on the likelihood that the factor of safety could be less than unity. These techniques, combined with sufficient site investigation data, might be used to support the adoption of lower factors of safety for the design of some slopes.

Lee and Charman (2004) estimate the probability of failure of a slope designed with a factor of safety of 1.5 to be between 10^{-5} and 10^{-6} per annum if model and parameter uncertainty are low. This contrasts with slopes designed with a factor of safety of 1.3, where the estimated failure probability is between 10^{-2} and 10^{-3} per annum. In both cases, failure probability could be higher if soil and groundwater conditions, the mechanism of failure, or the effects of human activity on the stability of the slope are poorly understood. The design of slopes in frontier areas where geotechnical experience is lacking, or excavations in stiff, high plastic clays continue to pose challenges, for example, but experience supports the assessment that engineered slopes with factors of safety greater than 1.5 tend to perform well and are generally considered "safe."

2.2 Hazard Probability and Partial Risk Approach

Hazard probability in this paper refers to the annual probability of landslide occurrence. In practice, approving authorities make decisions based on the probability of a landslide reaching an existing or proposed development. This is more accurately referred to as the "encounter probability" or "partial risk."

In British Columbia, hazard acceptability thresholds for development approvals were first put forward by Cave (1992), a former Director of Planning for the Regional District of Fraser-Cheam (now FVRD). The thresholds address a range of landslide types, including debris flows, small landslides, rock fall, and large rock avalanches. Recognizing that different landslide types with the same probability can impose different levels of risk, threshold levels were set based on consideration of the hazard type. A distinction was also made between types of development, ranging from minor repairs and reconstruction to permitting of new buildings and approval of new subdivisions, which influences the number of additional people exposed to landslide hazards. Depending on the landslide type and the type of proposed development, unconditional approval can be granted for encounter probabilities ranging from 1:500 to less than 1:10,000.

Most of British Columbia was deglaciated about 10,000 years ago, providing a convenient means of identifying locations where the probability of landslide occurrence is likely less than 10^{-4}. Confirming the absence of Holocene landslide deposits and ruling out the possibility of large first-time failures, such as might be indicated by sagging slopes, constitutes one of the simplest forms of a landslide safety assessment. Provided this type of assessment is carried out by suitably qualified professionals it will likely result in a level of landslide safety that meets the expectations of approving authorities and the public. Unfortunately, in mountainous terrain it is often quite difficult to identify ground completely free of evidence of past landslide activity.

2.3 Risk of Loss of Life Approach

Where rapid landslides are possible, the potential for loss of life may represent the overriding consequence of concern to approving authorities. Criteria based on the risk of loss of life are used to guide the development approval process for landslide prone areas in Hong Kong and Australia, and form part of industrial health and safety regulations in the U.K. and the Netherlands (AGS 2000; AGS 2007; Ale 2005; Leroi et al. 2005; Whittingham 2008). Two measures of risk are considered: risks to individuals and risks to groups (or societal risk).

Individual risk addresses the safety of individuals most at risk at an existing or proposed development. When considering the exposure to a single landslide hazard, this is calculated according to Equation 1:

$$R = P_H * P_{S:H} * P_{T:S} * V * E \qquad [1]$$

where:

- P_H = the annual probability of the landslide occurring;
- $P_{S:H}$ = the spatial probability that the landslide will reach the individual most at risk;
- $P_{T:S}$ = the temporal probability that the individual most at risk will be present when the landslide occurs;
- V = the vulnerability, or probability of loss of life if the individual is impacted; and
- E = the number of people at risk, which is equal to 1 for the determination of individual risk.

Where risk of loss of life criteria are used in countries with a common law legal system, the maximum tolerable level of risk for new development is typically 10^{-5} per annum for the individual most at risk (Leroi et al. 2005). A distinction is often made between new and existing development, with risks as high as 10^{-4} per annum sometimes tolerated for existing development.

When the expected area impacted by a landslide is small and density of development is low, approval decisions are typically governed by the estimated level of individual risk. When large groups are exposed to a hazard, however, societal risk will often determine if development is approvable from a risk perspective.

Societal risk considers the total potential for loss of life when all people exposed to a hazard are accounted for. For a single landslide hazard societal risk can be estimated using Equation 1, with 'E' set to the number of people at risk. If the spatial and temporal probabilities and the vulnerability varies across the population exposed to the hazard the group will need to be subdivided according to uniform level of exposure with the results summed to arrive at a total expected number of fatalities should the landslide occur.

Societal risk estimates are presented on graphs showing the expected frequency and cumulative number of fatalities, referred to as F-N curves (Figure 1). F-N curves were originally developed for nuclear hazards (Kendall et al., 1977), where the purpose was to illustrate risk tolerance thresholds reflecting societal aversion to multiple fatalities during a single catastrophic event. The graph is subdivided into four areas representing unacceptable risk, tolerable risk which should be reduced further if practicable according to the ALARP principle, risk that is considered broadly acceptable, and a region of low probability but with the potential for >1000 fatalities that requires intense scrutiny. From the perspective of potential loss of life, development might be approved if it can be demonstrated that risks fall in the ALARP or Broadly Acceptable regions on an F-N curve.

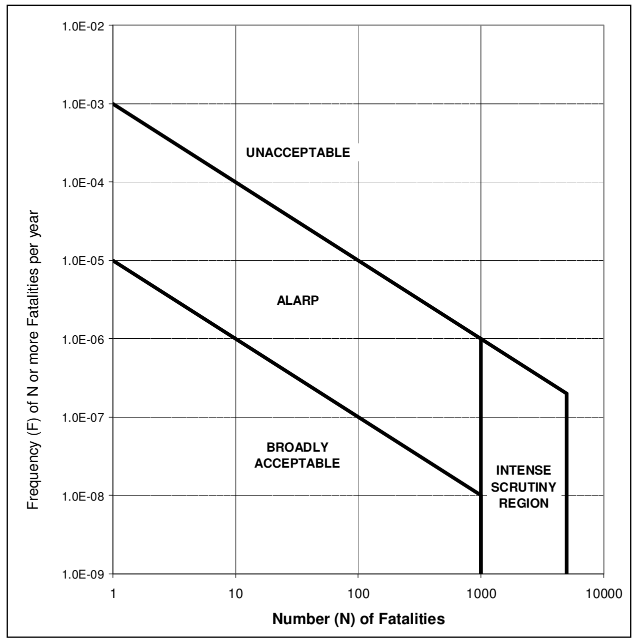

Figure 1. Example F-N Curve for Evaluating Societal Risk

2.4 Selection of an Assessment Method

In some instances an approving authority may have adopted a single method of evaluating the level of landslide safety, hence no choice is required. In other jurisdictions multiple options may be available or guidance on which method to use may be absent. Where a choice must be made, how should a qualified professional determine which method of landslide safety assessment is most appropriate? This section presents a thought process which may form the basis for a standardized approach.

Limit equilibrium slope stability analysis can be used to obtain reliable estimates of the factor of safety where the source and mechanism 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. The Observational Method, by which predicted ground conditions and slope behaviour are made in advance and verified during construction and management of a slope, helps to minimise the effects of parameter, model, and human uncertainty (Morgenstern 1995). When used in conjunction with the Observational

Method, factors of safety have been applied successfully for decades to the design and management of "engineered" slopes such as cuts, fills, and retaining walls, and for the design of structures located on or at the crest of potentially unstable slopes. Slope stability analyses, in conjunction with liquefaction susceptibility and lateral spreading or deformation analyses can be used to assess the level of landslide safety under earthquake loading scenarios. The factor of safety approach can also be used 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.

Where existing or proposed development is located down slope of a potential landslide hazard (and not on the slope itself), hazard probability or risk of loss of life may offer a more suitable means of assessing landslide safety. The application of hazard probability may be limited to situations where it can be demonstrated that landslides do not pose a credible threat to an existing or proposed development. Examples include:

- sites where Holocene-age landslide deposits are absent and no potential source of large-scale instability can be identified up slope;
- sites located outside of the zone of impact of the maximum credible landslide hazard, such as locations outside of the rock fall shadow below a well-defined rock fall source area; and
- situations where the debris from the maximum credible landslide hazard can be prevented from reaching a site through the design and construction of physical barriers such as ditches, berms, or catch nets.

For all other situations it may be more appropriate to conduct a quantitative assessment of the risk of loss of life and encourage the approving authority, in collaboration with the qualified professional, to evaluate the level of landslide safety by comparing the results against published risk tolerance criteria. These special situations generally involve:

- sites located at the base of slopes or in the potential runout zone of a credible landslide hazard;
- sites where it is not practical to demonstrate that the slope stability factor of safety for all credible landslide hazards is greater than the acceptance criteria; and
- sites where providing for physical protection against all credible landslide impacts is not practical.

Where provincial or municipal guidance is lacking, APEGBC (2008) recommends evaluating risk estimates against other published criteria. Examples include those used in Hong Kong, Australia, and the U.K., namely, a maximum tolerable risk to individuals of 10^{-4} per annum for existing development and 10^{-5} per annum for new development, and use of the F-N curve presented in Figure 1 to evaluate societal risk.

Some jurisdictions may prefer to use qualitative terms to express and evaluate the results of quantitative risk assessments. The Australian Geomechanics Society provides recommended qualitative terms that are reproduced in Table 1 (AGS 2007). Using these qualitative descriptors, "Moderate" risk represents the limit of tolerability for existing development.

Table 1. Qualitative Descriptors for Risk of Loss of Life (after AGS 2007)

Annual Probability of Death for the Individual Most at Risk	Qualitative Descriptor
$>10^{-3}$	Very High
$10^{-4} – 10^{-3}$	High
$10^{-5} – 10^{-4}$	Moderate
$10^{-6} – 10^{-5}$	Low
$<10^{-6}$	Very Low

3 CONSIDERATIONS FOR USE OF RISK TOLERANCE CRITERIA

In the preceding discussion various options for determining and evaluating the level of landslide safety at existing and proposed residential developments were reviewed and scenarios amenable to use of risk-based criteria were identified. In the sections that follow a number of social and technical considerations are presented that may help guide decision makers and qualified professionals with the adoption and/or application of risk of loss of life tolerance criteria as a means of managing landslide safety.

3.1 Origins and General Principles

The use of risk of loss of life tolerance criteria originated in the United Kingdom and the Netherlands during the 1970's and 80's in response to the need to manage risks from major industrial accidents (Ale 2005). Hong Kong adapted the United Kingdom criteria for the management of landslide hazards, and similar approaches have been applied in Australia, Switzerland and Austria.

While risk tolerance levels vary amongst jurisdictions and the evaluation criteria for individual and societal risk are different, some common general principles apply (Leroi et al. 2005):

- the incremental risk from a hazard to an individual should not be significant compared to other risks to which a person is exposed in everyday life;
- the incremental risk from a hazard should be reduced wherever reasonably practicable, i.e. the As Low As Reasonably Practicable (ALARP) principle should apply;
- if the possible number of lives lost from an incident is high, the likelihood that the incident might occur should be low. This accounts for society's particular intolerance to many simultaneous casualties, and is embodied in societal tolerable risk criteria; and,
- higher risks are likely to be tolerated for existing developments than for new proposed developments.

In the United Kingdom, maximum tolerable risk for individual members of the public is set by the Health and Safety Executive (HSE) at 10^{-5} per annum for new development. The upper limit of tolerability is set at 10^{-3} per annum for workers based on the assumption that the risk faced by workers is somewhat voluntary (Whittingham 2008).

In the Netherlands, maximum tolerable risk is 10^{-6} per annum. In practice, however, Ale (2005) has shown that the United Kingdom and Netherlands risk tolerance criteria are very similar as a result of the different legal systems employed by the two countries.

The United Kingdom (and Hong Kong and Canada) are governed by the Common Law legal system while the Netherlands' system is based on Napoleonic law. In the Common Law system it is not legal to put workers or the public at risk. Meeting the minimum regulatory risk requirements is one means of reducing legal liability but the courts impose a further test of gross disproportionality (Ale 2005). To meet this test, the entity that permitted a risky situation to develop that resulted in a loss of life must demonstrate that the cost to achieve a lower level of risk would have been disproportionate to the benefits. The concept is embedded in the ALARP principle that requires that risks be reduced to as low as reasonably practicable. When applied to a level that might meet the satisfaction of the courts, the ALARP principle often results in a maximum level of individual risk that is 10^{-6} per annum or less. In the Netherlands, Napoleonic law only requires that regulatory standards be met. Consequently, risk levels in the two jurisdictions are very similar in most circumstances.

3.2 Comparison with Canadians' Risk in Everyday Life

While there is precedent for using F-N curves and maximum tolerable risk levels for individuals to evaluate the level of safety posed by landslides, in Hong Kong and Australia, it is logical to question whether it is appropriate to apply similar tolerable risk levels in British Columbia. Comparison of the Hong Kong landslide risk tolerance criteria against Canadians' level of background risk suggests these criteria may indeed be appropriate.

A person's annual risk of loss of life depends on a number of factors including their age, occupation, general state of health and other environmental factors. Statistics Canada (2005) reports the average Canadian mortality rates by cause. Between 2000 and 2005 the age-standardized risk of loss of life by all causes was about $6*10^{-3}$ per annum, or about a 1:175 chance per year. The average risk from accidental causes was about $4*10^{-4}$ per annum, and the average risk from automobile accidents was about 10^{-4} per annum.

Table 2 compares the incremental increase in the average Canadian's risk of loss of life if exposed to various levels of landslide risk. As discussed earlier, a general principle in establishing landslide risk tolerance criteria is that the incremental risk from a hazard should not be significant compared to other risks in everyday life. Although 'significant' is not defined, inspection of the percentage increase in risk from various levels of landslide exposure suggests that the incremental risk is low (<0.2%) for landslide risk levels less than 10^{-5} per annum.

Table 2. Canadians' Incremental Risk of Loss of Life (per annum) under various Landslide Risk Levels

Incremental Risk	Total Average Risk	% Increase
0	$5.637*10^{-3}$	0
10^{-6}	$5.638*10^{-3}$	0.018
10^{-5}	$5.647*10^{-3}$	0.18
10^{-4}	$5.737*10^{-3}$	1.8
10^{-3}	$6.637*10^{-3}$	18

3.3 Application in North Vancouver

In the early morning of January 19, 2005, prolonged and high intensity rainfall triggered a fill-slope failure at the crest of the Berkley Escarpment in the District of North Vancouver (DNV). The landslide destroyed two homes at the base of the slope, seriously injuring one person and killing another. A review of previous engineering reports, published literature, and aerial photographs revealed that five other fill-slope failures had occurred along the escarpment since 1972. Concerns over the potential impact of future landslides prompted DNV Municipal Council to commission a landslide risk assessment and implement a risk management program. The case history is described in Porter et al. (2007) with key details reproduced below.

A framework for landslide risk management compatible with Canadian guidelines (CAN/CSA Q850-97) was tailored to meet DNV's requirements (Figure 2). The program was implemented in phases: Phase I included risk estimation and risk evaluation; Phase II included evaluation of risk control options and development of a remediation strategy; and Phase III involved execution of the remediation program and re-evaluation of the landslide risks.

Two measures of risk were estimated: the risk to individuals on all occupied properties located on and below the escarpment crest, and the societal risk for hypothetical flow slide source areas. Risk estimates were summed up for the entire escarpment and calibration of the risk model was undertaken so that results matched the historical record.

Calibrated individual risk estimates exceeded an incremental risk of fatality of 10^{-4} per year at 43 properties, including two that were located at the crest of the escarpment. Due to the red shading used to highlight these properties on maps made available to the public, these properties became known as the 'Red Zone' properties.

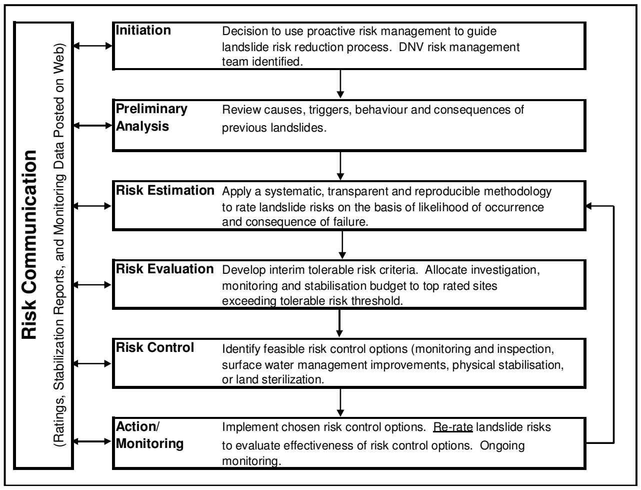

Figure 2. Risk management framework (after CAN/CSA Q850-97

Based on the results of the risk assessment, consultants' recommendations, and informal feedback from the public, the Municipal Council determined that the Hong Kong landslide risk tolerance criteria would be used to prioritise remedial works on the Berkley Escarpment. Measures were required to reduce individual risks to less than 10^{-4} per year and to move all hypothetical flow slide source areas out of the 'unacceptable zone' and into the 'ALARP zone' when plotted on the F-N curves utilised in Hong Kong.

Public response to the results of a quantitative landslide risk assessment (QRA) was a considerable source of uncertainty at the outset of the study due to the lack of precedent in British Columbia. Residents living at the top of the Berkley Escarpment tended to argue that the risk estimates were somewhat conservative, perhaps in part because of concern that they would bear the costs of any required mitigation. Residents living at the base of the escarpment tended to argue that the risk estimates were not conservative enough, perhaps in part because they were the ones most vulnerable. However, in general it appeared that there was public support for the process, and presentation of results in the form of risk of fatality did not prompt public outcry. In spite of the published risk levels there has been a change in ownership for several properties along the escarpment, suggesting that at least some members of the public are willing to tolerate these levels of landslide risk. This would suggest that other Canadian communities may be amenable to the application of QRA to landslide and other geohazard risks.

Parallel to management of landslide risk along the Berkley escarpment, quantitative risk estimates were made for a number of existing developments on debris flow fans throughout the District. Most properties had tolerable individual and societal risk levels when evaluated using the Hong Kong criteria, though risks at some properties were determined to be unacceptably high. The results of these estimates have been made public and development of a real-time debris flow warning system is currently being tested to help manage debris flow risk.

In 2007 DNV convened a public task force to review and make recommendations on the landslide risk tolerance thresholds. Upon completion of a number of training sessions, public meetings, and public survey, the Task Force recommended that DNV continue to use the Hong Kong criteria for individual risk.

DNV is currently working on an implementation plan to formally adopt the landslide risk tolerance criteria for new and existing developments. Experience to date suggests the criteria for existing development are generally achievable, but use of the more stringent criteria for new development faces some challenges. Many of these are anticipated to arise from questions over what constitutes "new development." It is known that residents at many homes currently face an individual risk from landslides between 10^{-4} and 10^{-5} per annum and, short of acquiring the properties and relocating the residents there is little that can be done to reduce these risks further. Major renovations, repairs, or reconstruction of homes on these properties potentially constitute 'new development' and may not be permitted if there is an associated requirement to reduce landslide risk to less than 10^{-5} per annum. One possible solution is to limit application of the more stringent criteria to the approval of new subdivisions and infilling of existing subdivisions.

In 2008 the Provincial Coroner issued a report on the 2005 landslide fatality. The report contained a number of recommendations to the Province, the Union of BC Municipalities, and APEGBC. Amongst recommendations to the province was a call to establish a legislated provincial standard for how landslide assessments should be conducted and coordination of the development of provincial landslide safety levels. The Coroner also recommended that a database of landslide hazard and risk information be created and made accessible to all stakeholders to facilitate informed decision-making.

3.4 Societal Risk Estimates and the Consultation Zone

The geographic area considered for a landslide safety assessment is known as the "consultation zone" (Geotechnical Engineering Office 1998). The consultation zone has been defined as a zone of standard extent that includes the area of a proposed development within the maximum credible extent of potential landslide hazards (Hungr and Wong 2007). In Hong Kong this typically corresponds to a 500 m wide strip of land at the base of a slope. Altering the size of the consultation zone can change the estimates of societal risk.

The current definition may be effective for proposed development in areas that are the responsibility of a single approving authority, but can be difficult to apply to areas that also contain existing development or that are the responsibility of more than one approving authority. This is often the case in British Columbia where responsibility of development approval has largely been transferred to the municipalities, and where new development often involves infilling of existing subdivisions. For example, consider a potentially unstable slope with both proposed and existing residential housing at the base. If only the area with proposed buildings is defined as the consultation zone, societal risk would be lower than if the entire development was considered, because the entire development contains more elements at risk. Which definition is more appropriate?

Furthermore, situations may exist where a municipal boundary or property line straddles an area potentially impacted by a landslide. While landslides do not recognize property or political boundaries, these boundaries do impose practical limitations on the approving authorities and qualified professionals charged with undertaking landslide assessments. One example includes limitations on access for the investigation of slopes above or adjacent to a subject property, especially where these 'off-site' slopes may be the dominant source of the landslide hazard. Another involves landslides with the potential to impact more than one municipality. While collaboration should be encouraged in these cases, the consultation zone should be defined in a way that allows one of the municipalities to proceed with the estimation of its societal risk without the cooperation of its neighbours.

In an attempt to balance these technical and political realities, the authors propose a more detailed definition of the Consultation Zone. *The Consultation Zone shall include all proposed and existing development in a zone defined by the approving authority that contains the largest credible area affected by landslides, and where fatalities arising from one or more concurrent landslides would be viewed as a single catastrophic loss.*

Examples might include a particular river escarpment, a single or coalescing series of alluvial fans, the area potentially impacted by a rock avalanche, or other areas defined by the community or approving authority. Determining the largest credible area affected by landslides would require an inventory of the hazards, estimation of landslide magnitude and frequency, and landslide runout analyses. This may not be known at the outset of a risk assessment unless regional landslide hazard maps have already been prepared.

3.5 Data Requirements and Limitations of Risk-Based Assessments

Quantitative estimates for risk of loss of life require estimates of the parameter values and associated uncertainties listed in Equation [1]. Often, data for model calibration are scarce. Guidelines and numerical models have been developed that can be used to help constrain estimates of the spatial probability of impact. For most residential development applications, the temporal probability for individuals will range between 0.5 and 1 and is not a significant source of uncertainty. Data from previous landslides can be used to constrain estimates of vulnerability for different landslide types and intensities (e.g. AGS 2000). Estimating the probability of landslide occurrence, however, can be very challenging and often represents the greatest source of uncertainty when conducting a quantitative risk assessment. The effects of earthquakes and changing conditions (e.g. urbanization, forest fires, beetle infestations, clearcut logging and climate change) pose additional uncertainties that may need to be accounted for in estimates of current and future landslide risk.

Access to historical landslide data, such as location, date of occurrence, causal and triggering factors, type, size, travel distance, and extent of damage, can be immensely helpful in reducing the uncertainty associated with assigning estimates of both landslide probability and risk. Calibration using data from other risk assessments for similar landslide processes and risk scenarios should be carried out whenever possible; however the data necessary for calibration are often scarce in British Columbia. Implementing the Coroner's recommendation to establish a province-wide (or national) landslide database would be a helpful step in this regard. Previous attempts to form and maintain such databases have failed due to a lack of funding and lasting dedication, but this might be mitigated if the initiative was supported at the provincial or federal level.

Budgetary constraints can often pose limitations on the reliability of landslide risk assessments. This is also true of landslide safety assessments based on estimates of factors of safety or landslide likelihood, and therefore budget should never be an overriding factor in determining which method of assessment is most appropriate. Conservative values can be assigned to the input parameters when data are lacking as a result of budgetary constraints or other factors. For example, obtaining a detailed frequency-magnitude relationship for a debris flow fan, or quantitative models of flow runout and intensity, might be beyond the scope of a small project (i.e. an individual house). In this case, partial risk estimates for individuals or groups would be summed based on fewer landslide magnitude-frequency categories and less detailed population groups, using reasonably conservative estimates of landslide magnitude, frequency, and intensity.

Professional judgement plays an important role in landslide risk assessment. Considerable judgement is required to recognize the types of landslide hazard that might occur, select the appropriate extent of the consultation zone, design the site investigation program, and assign reasonable ranges of values to the input parameters. The importance of experience and judgement is not unique to risk-based assessments of landslide safety.

In the authors' experience, event trees are a helpful means of checking that all reasonable risk scenarios are included in a risk-based assessment and tracking the risk estimate calculations. They help to ensure transparency and repeatability of the methods used and can serve as a visual tool for risk communication with decision makers.

Even under the best of circumstances it is difficult to estimate risks associated with events that occur very infrequently. For example, due to limitations in data and assessment methodology, the margin of error associated with estimates of landslide probability can be expected to increase significantly for event probabilities less than about 10^{-3} per annum (Morgenstern 1995). When combined with the uncertainties associated with estimates of spatial and temporal probability and vulnerability, it may not be possible to defensibly differentiate between calculated levels of landslide risk that are less than about 10^{-5} per annum under different development or mitigation scenarios, for example, and decision makers must be made aware of these limitations. Use of qualitative terms representing values that range over an order of magnitude to express the results of quantitative risk assessments may help to convey some of the uncertainty associated with estimated risk values.

4 DISCUSSION AND SUMMARY

This paper recommends that a consistent level of landslide safety be established at a provincial, if not national level. Consistent landslide assessment methods and acceptance criteria would greatly benefit the process of residential development in areas potentially subject to landslides.

If provincial or national landslide standards are developed, they will need to be sufficiently flexible to allow for development in a wide range of geographic environments subject to different types of landslides, as well as differences in the amount of historical data and local knowledge that are available. It is recommended that landslide safety standards consider three possible approaches to the assessment of the level of safety, including factor of safety, hazard return period, and risk of loss of life. Some guidance is provided here as to which method is best applied under different circumstances.

Where risk of loss of life is determined to represent the most appropriate measure of landslide safety, the Hong Kong and Australia landslide risk tolerance criteria appear to provide a useful starting point for evaluating landslide risk at existing and proposed development in British Columbia. It is recognized, however, that the Hong Kong regulatory and physiographic situation cannot be directly compared to all situations in British Columbia where developable land is relatively more abundant and risk can be avoided to a greater degree.

An expanded definition of the “consultation zone” is provided to allow estimation of societal risk over a broader range of development scenarios than addressed by the definition currently used in Hong Kong. Special consideration will need to be given to the definition of “new development” so that the safety criteria can be applied in a fair and balanced manner.

The paper addresses some of the limitations of risk-based assessments, particularly where knowledge of past landslide processes and frequency is limited, and highlights the need for compilation and sharing of landslide data to improve the reliability of these assessments.

Storing landslide monitoring data in a publically accessible database may, in the long-term, also help to improve our understanding of landslide frequency and triggers, allowing for better calibration of risk estimates.

Combining these efforts in Canada with the development and implementation of a unified geohazard and risk mapping approach would further improve consistency to the way public safety is managed. This type of unified approach has been used in other countries for over 30 years, involving the production of geohazard and risk maps using a common scale, legend and symbology. For example, Switzerland is following this approach which will require that geohazard and risk maps be prepared for all of its towns and villages by 2013.

Landslide safety assessments can be very involved and often require that a significant budget be allocated for site investigation and analysis. Budget limitations should not determine the level of landslide safety. Determining the budgetary requirements of a landslide assessment involves some understanding of the scale and intensity of study expected by the approving authority in order to ensure a consistent minimum level of safety. If such understanding is lacking, the assistance of government and / or the professional associations should be sought in formulating adequate work scopes and terms of reference for landslide safety assessments.

When budget constraints for existing development do not allow for construction of engineering solutions to reduce risk to acceptable levels, alternative risk management strategies including public education and awareness, and landslide warning systems should be contemplated, at least on an interim basis, until other solutions can be found.

While this paper focuses on residential development, the assessment methods presented here can likely be expanded to the management of landslide safety affecting workers and the public associated with industry, such as forestry, mining, and power generation, linear facilities such as roads and railways, and public areas such as campgrounds and historical sites. This will require further review of the distinction between risk to workers and risk to the public that currently exists in practice in the United Kingdom, and also the methods to evaluate societal risk for facilities such as highways where very large numbers of individuals are exposed to what usually amounts to a very low level of risk.

A growing population in British Columbia and Canada will continue to increase the demand for safely habitable spaces. At the same time, society’s tolerance for risk appears to be diminishing. British Columbia, with its unique topography, geology and geomorphology, has a disproportionately large share of landslide hazards. “Safe” development in this environment requires a unified approach to the management of landslide hazard and risk. This paper has outlined some key elements of such an approach, including applicable methods for assessing landslide safety and potential hazard or risk acceptance criteria associated with each method.

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