RISK MANAGEMENT FOR URBAN FLOW SLIDES IN NORTH VANCOUVER, CANADA

BREAKING GROUND IN THE NATION'S CAPITAL · L'AVENIR SUR UNE BASE SOLIDE DANS LA CAPITALE NATIONALE
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THE DIAMOND JUBILEE
LE JUBILÉ DE DIAMANTS

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ABSTRACT
In the early morning of January 19, 2005, heavy rainfall triggered a rapid fill-slope failure at the crest of an escarpment in the District of North Vancouver, Canada. The landslide destroyed two homes, killing one person and seriously injuring another. Following the landslide, a program was implemented to quantify and manage the risk of loss of life arising from future fill-slope failures as well as facilitate communication amongst stakeholders. Quantitative risk tolerance criteria developed for application in Hong Kong were adopted, on an interim basis, to prioritise remediation efforts.

RESUME
Tôt le matin du 19 janvier 2005, des pluies abondantes ont déclenché la rupture rapide d'une pente de remblai à la crête d'un escarpement dans le district de North Vancouver, Canada. Le glissement détruisit deux maisons, tuant une personne et en blessant sérieusement une autre. Suite au glissement de terrain, un programme fut implanté pour quantifier et gérer le risque associé avec la perte de vies relié à de futures ruptures de pentes de remblai et pour faciliter la communication entre les intervenants. Les critères quantitatifs de la tolérance des risques développer pour leur application à Hong Kong furent adoptés, sur un plan temporaire, pour prioriser les efforts de rectifications.

1. INTRODUCTION

Urban landslides have occurred in the Lower Mainland of southwestern British Columbia, Canada, since the region was first developed in the 1800s. The landslides typically initiate along escarpments comprising unconsolidated Pleistocene sediments (Eisbacher and Clague 1981) and take the form of block falls, caving erosion, debris slides, and debris flows (Hungr and Smith 1985). Where residential development has encroached upon slopes, the risks of fatality and property damage have increased. However, until recently, few attempts to quantify and evaluate landslide risks were undertaken in British Columbia.

In the early morning of January 19, 2005, heavy 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.

This case history describes the development and implementation of the landslide risk management program. Further details are provided in engineering reports that were made available to the public (BGC 2006a, BGC 2006b). It is hoped that this paper will assist others who attempt to carry out similar studies.

2. THE BERKLEY ESCARPMENT

2.1 Location

DNV comprises urbanized and undeveloped land located north of the City of Vancouver, and between the municipalities of West Vancouver and Port Moody. The Berkley Escarpment is situated within the DNV on the east side of the Seymour River, and between Riverside Drive and Berkley Avenue (Figure 1). The escarpment is approximately 2 km long and 60 m high, with slopes typically ranging from 30 to 45^{o}. The slopes are covered by second growth red cedar, hemlock, alder and maple.

2.2 Climate

DNV receives, on average, approximately 2,400 mm of rainfall annually, with most of this falling during the period November to February. During this period the area is subject to 'pineapple express' tropical storms that can produce more than 100 mm of rainfall with intensities exceeding 15 mm per hour. These storms often trigger landslides throughout the Lower Mainland. For example Eisbacher and Clague (1981) identified 27 landslide triggering storms affecting the Vancouver area in the period 1900 to 1979.

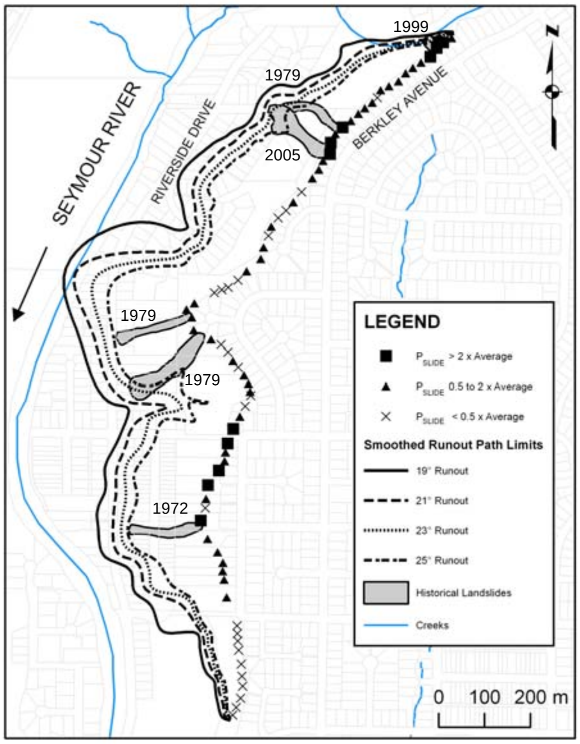

Figure 1. Location map showing study area, historical landslides, hypothetical source areas, and runout angles beneath the crest of the escarpment

2.3 Surficial Geology

The regional surficial geology is a product of multiple glacial events and past sea levels that were up to 200 m above present-day. Sediments deposited under these conditions over the past 30,000 to 40,000 years are exposed at various locations in the lower Seymour and adjacent watersheds (Figure 2). Near the crest of the Berkley Escarpment, Pleistocene deposits are typically overlain by colluvium and fill.

Strength and permeability contrasts between the fill and colluvium, and between the underlying Capilano glaciomarine sediments and Vashon Drift till, contribute to the potential for slope failures near the escarpment crest

Most of the fill—derived locally from glaciomarine sediments—contains sand- to cobble-size fragments of very stiff silt. The coarse components are usually supported in a matrix of fine sand that is typically loose to compact. The total thickness of fill is highly variable, and was observed to range from approximately 1 to 4 m at the escarpment crest.

The colluvium is derived from the glaciomarine sediments and lodgement till. Near the crest of the slope it is very similar in nature to the fill, while at lower elevations it contains a greater proportion of coarse sand and fine gravel.

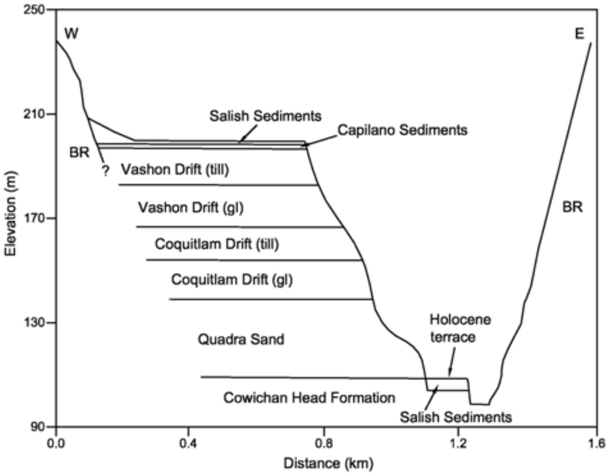

Figure 2. Typical stratigraphy of Pleistocene sediments found in the vicinity of the Berkley Escarpment (after Lian and Hickin 1993)

Capilano glaciomarine sediments are usually present beneath the fill. At the top of the unit the soils are often highly weathered, resulting in softening and a complete loss of structure. At depth, the soils comprise laminated sands, silts and clays that are stiff and only break down to silt-size particles with difficulty under finger pressure. The glaciomarine sediments generally have a lower permeability in the vertical direction than the overlying fill, giving rise to the potential for perched water tables during periods of intense rainfall.

Vashon Drift lodgement till underlies the glaciomarine sediments at all locations along the escarpment. The till is extremely dense and is relatively strong and impermeable compared to the overlying soils.

2.4 Residential Development

Timber harvesting was carried out across much of the Berkley Escarpment prior to about 1940. Homes were constructed along the crest of the escarpment starting around 1950, and along the base of the slope starting around 1960. Often the lots were levelled by pushing or end dumping local and imported materials over the crest of the escarpment, along with soils excavated to construct house foundations. In the process, tree stumps and other organic debris were often incorporated in the fill. Retaining walls, many comprising timber cribbing or concrete blocks, were constructed in several locations.

A storm sewer system was constructed along the crest of the escarpment in the 1980s, although until recently only a small percentage of the homes were connected to it. In many cases, roof, and even street runoff, was uncontrolled and allowed to flow over the slope.
Development has continued to the present day and currently about 75 homes are perched along the crest of the slope while an additional 75 homes are situated at the base.

2.5 Historical Landslides

Since 1972, four storms—December 1972, December 1979, January 1999, and January 2005—have triggered at least six landslides near the crest of the Berkley Escarpment (Figure 1). The four-week antecedent rainfall leading up to each landslide and the amount of rainfall generated by each storm are shown in Table 1.

Table 1. Antecedent and storm rainfall

Date	Antecedent Rainfall	Storm Rainfall
Dec 25, 1972	327 mm	135 mm
Dec 17, 1979	325 mm	135 mm
Jan 14, 1999	229 mm	79 mm
Jan 19, 2005	105 mm	175 mm

All six of the historical landslides appear to have originated in fill, quickly transforming into extremely rapid earth flows, referred to as flow slides. They entrained loose, partially saturated colluvium as they travelled down the steep escarpment slopes. Most of the slides had runout angles ranging from about 21 to 23^{o}. One of the 1979 flow slides, and the January 2005 flow slide caused damage to homes at the base of the escarpment.

3. RISK MANAGEMENT

3.1 Objective

In response to the events of January 2005, DNV Municipal Council implemented a risk management program to quantify and reduce the risks from future flow slides along the Berkley Escarpment.

The consequences from past flow slides were numerous and included injury, fatality, property damage, loss of property value, and litigation costs. A decision was made to focus on the risk of fatality since this consequence was deemed the most appropriate factor against which to prioritise requirements for risk management.

3.2 Traditional Approaches

Traditionally, Canadian engineers and geoscientists manage the risks from urban landslides by the use of a factor of safety against slope failure. A factor of safety greater than 1.5 is often adopted in an attempt to address uncertainty related to input parameters (shear strength and groundwater conditions), model uncertainty, and the consequences of failure.

Increasingly, population growth in urban centres has resulted in the development of properties beneath slopes like the Berkley Escarpment where the local factor of safety may exceed 1.5, but where the factor of safety up slope may fall below 1.5 under certain conditions, such as during periods of heavy rainfall or following the deterioration of retaining structures. This poses a number of challenges. The factor of safety does not in itself provide information on the likelihood that a landslide will impact a development if one occurs, nor does it provide information on the consequence of the impact. In many of cases, it may not be practical to calculate factors of safety against failure for all slopes and landslide mechanisms situated above a development, nor will it be practical to remediate all slopes so that the factor of safety always exceeds 1.5.

In some cases, hazard return period has been used to guide approvals for residential development and modification in areas potentially subject to landslides and floods (e.g., Cave 1992). While this approach addresses some of the shortcomings of the factor of safety approach, embedded in the tolerable return periods are assumptions about the likely consequences of failure, which affects the method's transparency and utility. Furthermore, the approach is limited in its ability to incorporate the effects of certain types of risk control measures and evaluations of the anticipated residual risks following mitigation.

3.3 Quantitative Risk Assessment

Quantitative risk assessment (QRA) involves:

- developing an inventory of landslide hazards;
- estimating the likelihood, consequence, and risk of landslide occurrence; and,
- evaluating whether the affected stakeholders can tolerate the estimated risks.

QRA allows the risks from different types of landslides to be compared with risks from other natural hazards as well as with hazards that stakeholders are exposed to in everyday life, such as daily commuting.

Risk management involves two additional steps:

- identification of options to reduce risk and an evaluation of their cost and benefit; and,
- implementation of the preferred options, including ongoing monitoring and re-evaluation.

The use of QRA to manage urban landslide risks in Hong Kong is well-documented; other organizations such at the Australian Geomechanics Society also provide recommendations for landslide QRA (AGS 2000).

Landslide risk management for the Berkley Escarpment was determined to be well suited to QRA:

- many landslide hazards were present, with no portion of the escarpment free from some level of landslide hazard;
- it was anticipated to be both difficult and expensive to remediate all slopes with a factor of safety less than 1.5 or to permanently sterilize all property where the potential for landslides existed;

- stakeholder expectations at the time demanded that results be presented in as transparent a manner as possible; and
- information necessary to calibrate quantitative risk estimates was available.

A framework for landslide risk management compatible with Canadian guidelines (CAN/CSA Q850-97) was tailored to meet DNV's requirements (Figure 3). 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.

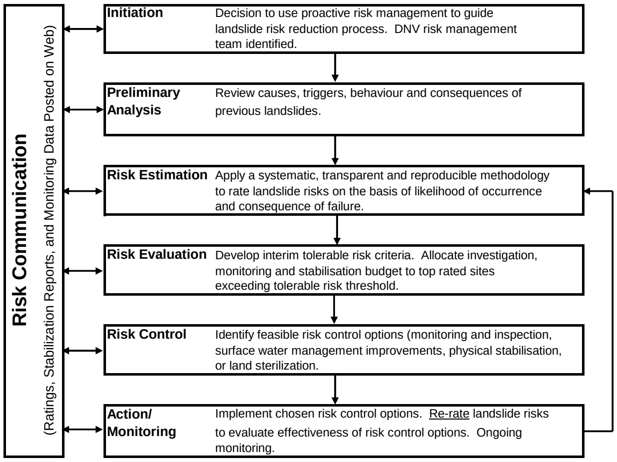

Figure 3. Risk management framework

3.4 Risk Estimation

The risk assessment addressed the potential for loss of life to house occupants as a result of flow slides initiating from loose fill and colluvium situated at the top of the Berkley Escarpment. Societal risks were estimated for each potential flow slide source area, and individual risks were estimated for each property at the crest and base of the escarpment. The following general equation was used to estimate the individual and societal risks:

$$\text{Risk} = P_H \times P_{S:H} \times P_{T:S} \times V \times E \qquad [1]$$

where:

- Risk is the expected number of statistical fatalities per year;
- P_H is the annual probability of a fill-slope failure leading to an extremely rapid flow slide;
- $P_{S:H}$ is the spatial probability of impact, given the slide occurs;
- $P_{T:S}$ is the temporal probability of impact, a measure of the probability of people being present at the time the slide occurs;
- V is the vulnerability of people impacted by the slide (a measure of the probability of surviving the impact); and,
- E is the number of people potentially at risk.

The procedures and assumptions used to estimate the potential for future flow slides and loss of life are provided in the sections that follow.

3.5 Hazard Probability (P_H)

Six rapid flow slides were known to have occurred along the Berkley Escarpment since 1972—a period of 33 years. This corresponds to an average failure frequency of 0.18, or about 1 slide every 5.5 years.

Previous flow slides had widths at the crest of the escarpment ranging from about 15 to 25 m. This is similar to the width of each backyard, which conveniently allowed for the subdivision of the escarpment into 75 potential landslide source areas with each corresponding to a property along the crest of the escarpment. The average annual likelihood of a flow slide initiating from each source area was approximately 2.4×10^{-3} or a return period of 1:420.

The likelihoods of flow slide initiation from each backyard along the escarpment were not expected to be equal. Based on an evaluation of the historical slides, three main factors were assumed to make a given slope more prone to failure than others:

- steep slope angles;
- the presence of thick layers of weak or collapsible soils such as loose fill and colluvium; and,
- surface and subsurface drainage conditions that promote high groundwater levels, especially during heavy rainfall events.

Slopes prone to landslides often show evidence of past deformation, including:

- an abundance of trees leaning down slope;
- tension cracks or small landslide scarps;
- leaning, bulging, or cracking retaining walls or other structures; or,
- settlement of soil along the crest of the slope.

Observations of past deformation were also incorporated in the risk assessment.

An algorithm was developed to adjust the estimated un-mitigated landslide likelihood up or down from the average value by as much as a factor of 10 using field observations gathered for each property. The simple algorithm took the form of:

$$P_H = [\text{slope score}] \times [\text{loose soil score}] \times [\text{water score}] \times [\text{deformation score}] \times [P_{\text{slide(avg)}}] \qquad [2]$$

Slope, loose soil, water, and deformation scores were assigned as shown in Table 2.

Table 2. Flow slide probability algorithm (modified to account for benefits of mitigation)

Slope Score	Loose Soil Score	Water Score	Deformation Score	Max / Min Scores
< 35^{o} = 0. 8 35 – 40^{o} deg. = 1.0 > 40^{o} deg. = 1.25	Approved mechanical stabilization at and below crest = 0.35 < 1m deep at crest and < 2m deep below crest = 0.35 < 2 m deep at and below crest = 0.5 > 2 m deep at or below crest = 1.0 > 2 m deep at and below crest = 2	All adjacent properties connected to storm sewer and street storm water properly managed = 0.35 Connected to storm sewer but adjacent properties not connected = 0.5, else: Runoff from backyard = 0.5 … and half roof = 0.75 … and full roof = 1.0 …and driveway = 1.25 … and street = 2	None observed = 0.5 Deformation at or below crest = 1.0 Deformation at and below crest = 2	Adjustment range = 0.05 to 10 (0.1 to 10 for the un-mitigated case) $P_{slide(avg)}$ = 0.0024 $P_{slide(max)}$ = 0.024 $P_{slide(min)}$ = 0.0001 ($P_{slide(min)}$ = 0.00024 for the un-mitigated case)

Many attributes influence the likelihood of flow slide occurrence, and because only a few slides are known to have occurred along the escarpment, there were insufficient data to assign attribute scores based on the results of rigorous statistical analyses. The attributes selected were ones that could be assessed through field inspection and completion of shallow hand-auger drill holes. Weightings were assigned based on engineering judgement. Key to producing defensible results was the calibration of the model to ensure that the calculated total annual probability of a flow slide somewhere along the escarpment was in line with the historical average.

Un-mitigated probability of failure estimates are shown in Figure 1.

3.6 Spatial Probability of Impact ($P_{S:H}$)

The nature of the 2005 landslide deposit and the damage it caused were spatially variable. Observed changes could be related to the angle above the horizontal plane as measured from the deposit to the slide headscarp, referred to here as the runout angle (Figure 1).

With runout angles steeper than 25^{o}, the January 19, 2005 landslide deposit comprised abundant large woody debris and mineral soil, and was typically greater than 2 m deep. Significant structural damage occurred to houses located within the slide path at runout angles steeper than 25^{o}. At runout angles between 23 and 25^{o}, the thickness of debris and amount of mineral soil decreased dramatically, as did the structural damage caused by the landslide. At runout angles between 21 and 23^{o}, landslide impacts were typically limited to flooding.

Based on the foregoing, a digital elevation model was used to determine the location of houses that were situated beneath the other historical flow slides, facilitating an estimate of the spatial probability of destructive impact as a function of runout angle (Table 3).

Table 3. Spatial probability of impact for houses situated at the base of the escarpment

Angle from House to Escarpment Crest	Spatial Probability of House Impact Leading to Damage $P_{S:H}$
> 25^{o}	0.67
23^{o} to 25^{o}	0.167
21^{o} to 23^{o}	0.083
19^{o} to 21^{o}	0.0025
< 19^{o}	Not evaluated

3.7 Temporal Probability of Impact ($P_{T:S}$)

In assessing the potential for loss of life at the base of the escarpment, it was assumed that house occupants were present an average of 12 hours per day during the rainy season when landslides are most likely to occur. This represents a temporal probability of impact of 0.5. It was also assumed that the individuals most at risk spend on average 16 hours per day in their homes.

3.8 Vulnerability (V)

The January 19, 2005 landslide was the only event to cause structural damage to houses at the base of the escarpment at a time when they were occupied. Two people were present in the house that was completely destroyed. One was killed while the other sustained very serious injuries, remaining in the hospital under intensive care for several months.

Five people were present in the second house that was impacted. Three of them were sleeping in the area that sustained structural damage. They received minor cuts and bruises as a result. The two people sleeping in the undamaged portion of the house were uninjured.

Based strictly on these observations, the vulnerability of occupants of houses struck by landslides of the type that occurred on January 19, 2005, is approximately one in seven, or a value of 0.14. However, it was acknowledged that the slide could have easily resulted in two or more fatalities amongst the seven people occupying homes that sustained damage, and consequently a vulnerability of 0.29 was adopted for the risk assessment.

3.9 Risk Estimates

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 each hypothetical flow slide source area. Risk estimates were summed up for the entire escarpment and calibration of the risk model was undertaken to match the historical record, defined as approximately one statistical fatality every 16.5 years.

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 (Figure 4). 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.

Societal risks were summed up for each hypothetical source area by assuming that four people occupy each home at risk and counting the number of homes situated beneath each potential slide. Twenty of the 75 hypothetical source areas were estimated to pose ‘unacceptable risks’ as would be plotted on an F-N curve like that used in Hong Kong. Another 37 other source areas plotted in the ALARP zone corresponding to a level where further efforts to reduce risks to as low as reasonably practicable are generally recommended Societal risk levels assigned to each source area are shown in Figure 4.

3.10 Risk Evaluation

The next step in the risk management process was the targeting of sites for mitigation by comparing the estimates against risk acceptance criteria. However, at the time the assessment was undertaken, quantitative risk acceptance criteria for landslides had not been defined for British Columbia or DNV. Instead, comparisons were made against criteria for other jurisdictions as reported in the published literature.

The Australian Geomechanics Society guidelines for landslide risk management suggest a tolerable limit of 10^{-4} per annum for individuals most at risk on existing slopes or developments, and a limit of 10^{-5} per annum for new developments (AGS 2000). Societal risks imposed by any given landslide hazard are deemed unacceptable if the expected frequency of one or more fatalities exceeds 10^{-3} per annum. The Hong Kong Special Administrative Regional Government has used, on an interim basis, the same tolerable limits for landslides from natural slopes (Leroi et al. 2005). In all cases, the ALARP principle applies—that is, risks should always be reduced to as low as reasonably practicable.

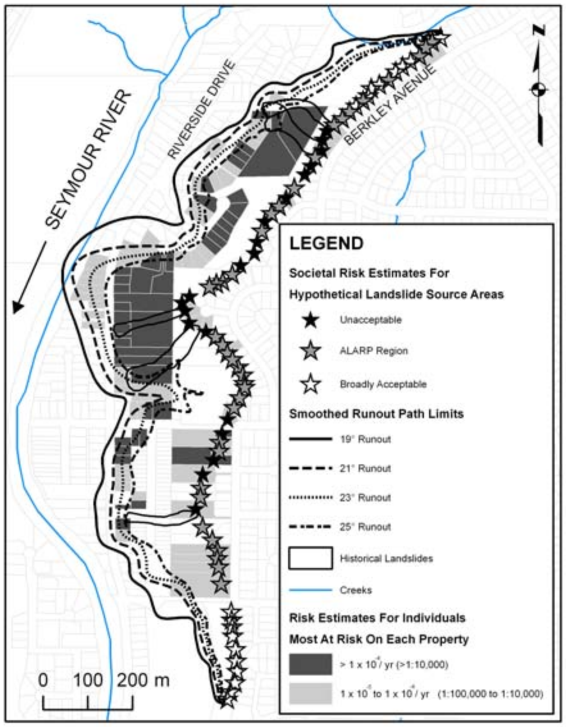

Figure 4. Un-Mitigated quantitative risk estimates

Though not specific to landslides, other jurisdictions such as the United Kingdom have adopted similar risk tolerance criteria for managing major natural and industrial accident hazards. For existing situations they have adopted a maximum tolerable risk of 10^{-4} per year. A description of the evolution of the U.K. criteria is provided by Ale (2005).

In addition, the published criteria were compared against other risks in an attempt to provide the public and the Municipal Council with a better understanding of what the numbers meant. An individual risk of 10^{-4} per year implies that individuals most at risk have a 1 in 10,000 chance of fatality for each year they are exposed to the hazard. This increment of risk is generally less than that of other risks individuals are exposed to in everyday life. For example, in 1997 the Canadian population as a whole faced a mortality rate of $7x10^{-3}$ (a 1 in 143 chance per year), which is about

70 times greater than the tolerable limit (Statistics Canada, 2005). A Canadian's annual risk of death from motor vehicle accidents in the same year was 10^{-4}, which coincidentally is identical to the Hong Kong tolerable limit for landslide risk at existing developments.

Based on the results of the risk assessment, consultants' recommendations, and informal feedback from the public, the Municipal Council determined that the interim 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.

3.11 Risk Control

Risk control for the Berkley Escarpment began with a brainstorming exercise to identify potential options to reduce the value of each component in the risk equation (Figure 5). This step was followed by a judgement-based assessment of the identified options to determine which were likely to be viable. Next, subjective estimates were made of the level of risk reduction that could be achieved through each option.

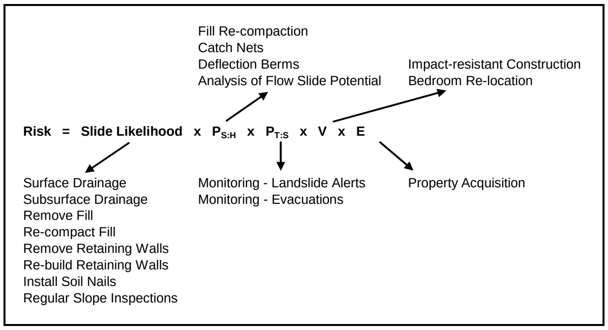

Figure 5. Risk control options

Benefits were measured in terms of the potential reduction to the risk of fatality. For a given option, this varied across the escarpment depending on the potential for landslides at each location and the position and number of houses exposed to each particular landslide hazard. For the purpose of illustrating potential benefits, risk reduction was quantified for a typical scenario posing a societal risk of 1.0×10^{-3} fatalities per year or approximately 3.1×10^{-2} fatalities for a 30-year period of exposure.

Each viable risk control option had an associated cost, usually including a capital cost for construction (including engineering costs) and an operating cost for ongoing inspection and maintenance. Typical capital and annual operating costs were estimated for each option. The net present value (NPV) of the combined total costs was also estimated for a 30-year period using a 5% discount rate.

Lastly, the cost-benefit ratio for each mitigation option was calculated according to:

$$\text{Cost-Benefit Ratio} = (\text{NPV of 30 Year Cost}) / (30 \times [\text{unmitigated risk} - \text{mitigated risk}]) \tag{3}$$

In general, risk control options with low cost-benefit ratios were anticipated to provide the greatest level of risk reduction for each dollar spent. As illustrated in Table 4, the analyses showed that drainage improvements, including the connection of roofs and perimeter drains to the storm sewer system, were most cost effective. Property acquisition and sterilisation were shown to be least cost effective.

Table 4. Estimated average cost-benefit ratios

Risk Control Option	Societal Risk of Fatality	Net Present Value of Option	Cost-Benefit Ratio ($ per Life Saved)
None	1.1×10^{-3}	-	-
Surface Drainage	3.6×10^{-4}	$14,500	$712,000
Subsurface Drainage	3.6×10^{-4}	$25,500	$1,251,000
Fill Removal	2.9×10^{-4}	$31,000	$1,352,000
Retaining Wall Removal	2.9×10^{-4}	$46,000	$2,021,000
Fill Compaction	2.9×10^{-4}	$53,000	$2,361,000
Debris Flow Barrier	5.3×10^{-4}	$77,500	$5,020,000
Property Acquisition	2.9×10^{-4}	$760,000	$34,500,000

3.12 Action/Monitoring

Based on the foregoing, a remedial action plan was developed and implemented. At the time the risk assessment was completed, a number of DNV capital projects related to risk control were already underway. These included the extension of the storm sewer system and connection of homes to it, the demolition of seven homes that were purchased with Provincial assistance, and the reshaping of the escarpment crest in the immediate vicinity to the 2005 landslide.

These activities left six properties at the crest of the escarpment that continued to pose unacceptable individual and societal risks. Topographic surveying, hand-auger soils investigations, and discussions with the affected property owners allowed 'field-fit' remedial designs to be prepared. In general, the remedial work involved removal of fill and deteriorating retaining walls, slope reshaping at approximately a 2:1 grade, and design and installation of bioengineering measures to control surface erosion. Remedial works were completed over the 2006 summer period.

Upon completion of all remedial works, the risks from future flow slides were reassessed. The total annual probability of flow slides from all locations along the escarpment crest was estimated to have been reduced to 5.3×10^{-2} per year, or a return period of 1:19. The total risk of fatality arising from flow slides was estimated to have been reduced to 1.1×10^{-2} per year, or a return period of 1:94.

3.13 Risk Communication

The Berkley Escarpment risk assessment involved a large number of stakeholders, including DNV staff, DNV elected and legal council, owners and occupants of the affected and nearby properties, potential home buyers, lenders, insurers, property tax authorities, and others. A number of measures were taken to satisfy stakeholder demands for an open and transparent process and timely dissemination of new information. Some of these included media releases and posting of technical reports on DNV's website as each phase of the risk management program was completed; open public meetings to present the results of each phase of the study and to respond to questions; and smaller group meetings open to the affected residents to understand their concerns and to discuss the details of the assessments.

4. DISCUSSION

To the authors' knowledge, the Berkley Escarpment landslide risk management program is one of the first applications of QRA to an existing residential development in Canada. Consequently, it provided a unique learning opportunity from which many observations can be made.

The technical aspects of the Berkley Escarpment QRA were not overly complex. Ground conditions along the length of the escarpment were relatively uniform and historical landslide occurrence and behaviour data were available to permit calibration of a risk model. Not all landslide safety assessments will have access to this level of historical data, and greater reliance may have to be placed on traditional investigation techniques and professional judgment if QRA is to be applied elsewhere.

Although the model was relatively simplistic, it provided information useful for the design of a mitigation program beyond that which would have been derived had the study stopped upon completion of slope stability analyses or a hazard assessment. Urbanized slopes pose unique challenges for slope stability assessment; the incorporation of uncertainty related to development history, future land modification, and the management of surface water are just some of these challenges. The judgement-based landslide likelihood algorithm allowed for the rapid incorporation of these important aspects, which represented a significant advantage over relying entirely upon slope stability analyses.

The assessment of the spatial probability of impact for homes located at the base of the escarpment relied heavily on topographic data. It was found that differences between the topography generated using aerial photographs and that generated using a LIDAR survey were significant enough to impact the predicted risk estimates. LIDAR survey results proved considerably more reliable in their prediction of the location of the crest and base of the escarpment.

Public response to the results of a QRA was a considerable source of uncertainty at the outset of the study due to the lack of precedent in Canada. 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. This would suggest that other Canadian communities may be amenable to the application of QRA to landslide and other geohazard risks.

At the time this paper was prepared, DNV Municipal Council was in the process of extending the landslide QRA methodology to other hazard types including earthquakes, floods, and forest fires. Quantitative risk estimates for a number of existing developments on potential debris flow fans had been prepared, and the formation of a task force to evaluate DNV's interim risk tolerance criteria was being contemplated.

Other natural hazard risk management initiatives included the construction of a GIS and database to store records of all historical technical reports within the DNV's files that reference natural hazard issues. This tool will aid District planners with the permitting and approval process for new developments and modification of existing developments. It will also provide valuable baseline data for calibrating regional hazard maps, if a decision is made to proceed in that direction.

5. APPLICATION TO OTHER RESIDENTIAL DEVELOPMENTS

In March 2006, the Association of Professional Engineers and Geoscientists of British Columbia

(APEGBC 2006) released a document entitled, “Guidelines for Legislated Landslide Assessments for Proposed Residential Developments in the Province of British Columbia.” It describes the legislation pertaining to residential development in areas potentially subject to landslides and provides guidelines for the assessment of landslide safety. It also provides a sample statement of assurance that includes a mechanism for comparing assessed landslide risk against local risk tolerance criteria, or where absent, against criteria developed for other jurisdictions. The APEGBC guidelines, in conjunction with the initiatives undertaken by DNV Municipal Council, may open up the possibility for application of QRA to other landslide issues throughout the province, and perhaps elsewhere across Canada.

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