BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

DISTRICT OF NORTH VANCOUVER

BERKLEY LANDSLIDE RISK MANAGEMENT

PHASE 2 ASSESSMENT OF RISK CONTROL OPTIONS

FINAL REPORT

PROJECT NO: 0404-002-04
DATE: May 11, 2006

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May 11, 2006

Project No. 0404-002-04

Mr. Jozsef L. Dioszeghy, P.Eng.
District North Vancouver
355 West Queens Road
North Vancouver, BC
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Dear Jozsef:

Re **Berkley Landslide Risk Management, Phase 2 Assessment of Risk Control Options**

Please find attached 20 bound copies and one digital copy of our above-referenced final report dated May 11, 2006. A copy has also been forwarded to Dr. N.R. Morgenstern, P.Eng., who was retained by BGC Engineering Inc. as an independent advisor for the study and as a reviewer of this final report.

Should you have any questions or comments, please do not hesitate to contact me at the number listed above.

Yours sincerely,
BGC ENGINEERING INC.
per:

Michael Porter, M.Eng., P.Eng.
Senior Geological Engineer

cc. Dr. Norbert Morgenstern

MJP/mjp

EXECUTIVE SUMMARY

Houses have been constructed at the top and bottom of a steep slope located east of the Seymour River, North Vancouver, herein referred to as the Berkley Escarpment. During construction and ongoing occupation of the houses, loose fill was placed at the top of the escarpment, locally oversteepening the top-of-slope and increasing the potential for a type of extremely rapid landslide that is referred to as a 'flow slide'. At many locations, other factors such as the concentration of surface runoff and deterioration of retaining walls also increase flow slide potential.

Following the January 2005 landslide, the District of North Vancouver commissioned a study to evaluate the risks from future flow slides originating from the crest of the Berkley Escarpment during periods of heavy rainfall, and options to reduce landslide risk. BGC Engineering Inc. was retained to carry out this risk assessment using a phased approach. The results of the first phase - risk estimation - were documented in a report dated January 13, 2006. The focus of that report was to highlight the factors contributing to the risks and to understand how the relative risks are distributed across the escarpment using a repeatable and transparent process.

This report documents the results of the second phase of study – risk control. Risk control involves the identification of options to reduce risk, and ranking of those options using cost-benefit analysis. The report also documents the most up-to-date base-case (i.e. pre-mitigation) risk estimates that incorporate the findings of additional site investigations, a LIDAR topographic survey, and other information made available to BGC since the Phase 1 report was issued.

Risk control is required where estimated risks exceed risk acceptance criteria established by the affected community. Quantitative tolerable risk or risk acceptance criteria for landslides have not been defined for British Columbia or the District of North Vancouver. In the absence of local criteria, individual and societal risk estimates for the landslide source areas were compared against criteria developed for other jurisdictions, namely, Hong Kong, Australia, and the United Kingdom. These societies have a relatively low tolerance for risk, and have considerable experience managing landslide risk in urban environments.

The updated base-case risk estimates differ slightly from those presented in the Phase 1 report; new information reported here allows the total risk to be distributed amongst slightly fewer properties. Forty-three properties are now identified where <u>individual</u> risk estimates exceed tolerable criteria defined for existing developments in Hong Kong. Occupants of these properties are exposed to an incremental risk of fatality exceeding 10^{-4} per year, or a 1 in 10,000 chance of fatality per year. 10^{-4} is, coincidentally, equivalent to the Canadian mortality rate arising from motor vehicle accidents. Of the 43 properties, two are located at the crest of the escarpment while the remainder are located at the bottom of the slope.

Based on comparisons with Hong Kong criteria for societal risk, 20 of the 75 hypothetical landslide source areas along the crest of the escarpment pose unacceptable base-case risk levels and 37 other source areas required further efforts to reduce risks to as low as reasonably practicable (ALARP).

Removal of the fill and retaining walls from the crest of the escarpment, as well as the control of surface drainage, is expected to reduce the potential for future flow slides to a value equal to or less than what it was prior to development. This, in conjunction with ongoing monitoring and public education, generally represents the recommended risk control strategy.

The impacts of recent property acquisitions, as well as storm sewer drainage improvement efforts and other remedial works currently underway will reduce the total risk exposure along the escarpment. Upon completion of these works in progress, the number of properties where the estimated individual risk will continue to exceed 10^{-4} per year will be reduced from 43 to 15; the number of source areas that will continue to present unacceptable societal risk levels, or that place individual at risks greater than 10^{-4} per year, will be reduced from 20 to five.

Assuming the Hong Kong risk acceptance criteria for existing developments represent an appropriate minimum target, additional remedial measures will be required on or adjacent to at least the five potential slide source areas that pose unacceptable risk levels, at an estimated total capital cost of $300,000. If remedial measures are to be implemented in stages, this would represent Stage 1 Remediation, following completion of the works in progress. Ongoing monitoring and inspection will be required to ensure that the remedial measures continue to perform as intended and that slope deformations are brought under control.

The ALARP principal requires that risks be reduced to as low as reasonably practicable, even where tolerable risk criteria are met. In light of this, an assessment of the costs and benefits of removing fill and retaining walls at all remaining slide source areas that give rise to individual risks exceeding 10^{-5} per year was undertaken. Risk control measures would be required on an additional 29 of the 75 potential slide source areas at an estimated total capital cost of about $1.4 million. If remedial works are to be implemented in stages, this would represent Stage 2 Remediation.

The completion of all works outlined about is recommended; however, **the scheduling of, and level of resources allocated to, mitigation work on the Berkley Escarpment should be prioritised based on an assessment of the resources available to carry out similar works throughout the District** at other locations where the risks to individuals are the same or higher.

In order to verify the ongoing effectiveness of the remedial measures, visual inspections, drainage inspections, and maintenance will be required at an estimated total annual cost of $40,000. Most of this inspection work will take place on private property. Additionally, if desired, ongoing operation of the rainfall and groundwater monitoring system will require an estimated annual operating budget of $20,000.

Due to the risks presented by the natural slope conditions, it is not deemed practicable to reduce individual risks from slides originating at the crest of the escarpment to values significantly less than 10^{-5} per year. Furthermore, there will remain a residual risk from potential mid-slope failures. This risk is perceived to be low, but has not been quantified at this point in time. As resources become available, and as other slopes presenting unacceptable risk levels throughout the District are brought under control, consideration should be given to quantifying the risks from potential mid-slope failures.

In most cases, completion of the works identified above is expected to reduce the potential for future flow slides to the point that individual risks are reduced to about 10^{-5} per year or less. In some cases, however, a period of monitoring will be required to demonstrate that remedial works have caused slope deformations near the crest of the escarpment to abate in order to justify reducing the estimated risks to 10^{-5} per year. Nine source areas appear to face this situation – these source areas show evidence of active slope deformation below the crest of the escarpment and homes are located directly below them at an angle $>25^{o}$. If deemed necessary, the installation of flexible debris flow barriers above the homes beneath these source areas, in conjunction with the works identified above, could immediately reduce individual risks to about 10^{-5} per year, regardless of whether or not slope deformations abate. The total capital cost to install these barriers is estimated at $675,000. If required, this could be carried out as Stage 3 Remediation, possibly in conjunction with an assessment of risks from potential mid-slope failures.

Regardless of the mitigation strategy that is adopted, maximum benefit and minimum cost will be realized if the design and construction of the remedial works on adjacent properties be carried out concurrently and as a collaborative effort amongst the stakeholders.

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LIMITATIONS OF REPORT

BGC Engineering Inc. (BGC) prepared this report for the account of the District of North Vancouver. It presents the results of quantitative risk estimates and recommendations for risk management for shallow, extremely rapid landslides initiating at or near the crest of a steep escarpment west of Berkley Road and East of Riverside Drive in North Vancouver. Other natural processes, such as flooding, soil erosion, debris flows, and deep-seated landslides are not included in this study. The risk assessment is limited to landslides triggered by intense rainfall. Landslides triggered by earthquakes, slope excavation, or other processes are not included in this study.

The material in this report reflects the judgement of BGC staff in light of the information available to BGC at the time of report preparation. Any use which a Third Party makes of this report, or any reliance on decisions to be based on it are the responsibility of such Third Parties. BGC accepts no responsibility for damages, if any, suffered by any Third Party as a result of decisions made or actions based on this report. In particular, BGC accepts no responsibility for changes in real estate values that may occur as a consequence of this report.

As a mutual protection to our client, the public, and ourselves, this report and drawings are submitted for the information of the District of North Vancouver. It is understood that the District of North Vancouver will make this report and drawings available to the community for the sole purpose of conveying current information about landslide risk management as limited in paragraph one, above. Authorization for any other use and/or publication of data, statements, conclusions or abstracts from or regarding this report and drawings is reserved pending our written approval.

Anyone in the community receiving a copy of this report and drawings is urged to recognize that these documents represent one of many steps in the risk management process as defined by Canadian Standards Association Guidelines (CAN/CSA-Q850-97). Conceptual designs for potential risk control measures have been prepared and order of magnitude costs have been estimated. The measures implemented at each location along the escarpment will need to be 'field fit' to suit the local conditions, and costs will vary from the average costs presented in this report. Ongoing inspection and monitoring will be required to ensure that the implemented risk control measures continue to perform as intended.

1.0 INTRODUCTION

The District of North Vancouver (DNV) retained BGC Engineering Inc. (BGC) to carry out a landslide risk assessment for the Berkley escarpment and to provide recommendations for risk management. The scope of work was outlined in a BGC proposal dated September 10, 2005 (BGC 2005a). It addresses shallow, extremely rapid landslides (referred to as flow slides) potentially initiating from the west side of approximately 75 properties located at the crest of the escarpment between the corner of Bendale Road and Berton Place (the southern limit) and the corner of Berkley Avenue and Whitman Avenue (the northern limit), as shown on Drawing 1.

This study has been carried out in Phases. A report issued to DNV on January 13, 2006 documents the results of a preliminary unmitigated landslide risk assessment, based on the first phase of investigations carried out as part of this study (BGC 2006). Since that time, additional investigations and analyses have been undertaken to:

- refine the estimates of unmitigated landslide risk based on the results of more detailed site investigation and other information made available to BGC since the Phase 1 report was issued. These unmitigated risk estimates are referred to the 'base-case' against which the benefits of potential mitigation strategies are compared; and,
- identify viable risk control options and estimate their potential benefit (in terms of risk reduction) and cost (capital cost and costs for 30 years of operation).

This report documents the results of the tasks identified above, and should be read in conjunction with our Phase 1 report. It provides a recommended strategy to reduce the societal risks from each landslide source area to less than 10^{-3} per year and the risks to individuals on all affected properties to less than 10^{-4} per year. The ALARP principal requires that, over time, risks be reduced to as low as reasonably practicable. Accordingly, additional options to reduce the risks to individuals are also provided. Analyses demonstrate it is practicable to reduce risks to about 10^{-5} per year or less by implementation of the measures outlined in this report.

In order to realize the full potential benefit of the risk control measures, each must be properly designed, constructed, and maintained. Recommendations for final design, quality control and assurance during construction, and ongoing maintenance are provided.

2.0 SITE INVESTIGATION RESULTS

BGC has carried out a wide range of site investigations along the Berkley Escarpment since the January 19, 2005 landslide occurred. Relevant details pertaining to slope stability near the crest of the escarpment were obtained through:

- detailed site investigations, including test pitting, hand-auger drilling, cone penetration testing (CPT's), groundwater and rainfall monitoring, micro-drainage surveys, soil laboratory testing, and slope stability analyses conducted in the immediate vicinity of the January 19, 2005 landslide headscarp (BGC 2005b, 2005c, and 2005d). These investigations were carried out at an elevated level of detail on behalf of other parties under separate scopes of work, in order to support an assessment of slide causation (made by others) and remediation requirements;
- slope inspections, including shallow hand-auger drilling at every property along the crest of the escarpment, carried out on behalf of DNV during Phase 1 of the landslide risk assessment;
- additional hand-auger drilling, CPT's, and installation of piezometers in select properties, carried out on behalf of DNV during Phase 2 of the landslide risk assessment; and,
- additional information made available to BGC, including geotechnical reports prepared by others, updated results from DNV drainage inspections, comments provided by land owners, and the results of a detailed topographic survey obtained through light detection and ranging (LIDAR).

2.1 Investigations in Immediate Vicinity of Slide Headscarp

Detailed site investigations and analyses carried out in the immediate vicinity of the January 19, 2005 landslide headscarp provide a general understanding of escarpment stratigraphy. Table 1 provides a summary of the typical soils encountered near the crest of the escarpment and their mechanical properties.

Table 1. Summary of Typical Soil Types and Properties

Soil Type	Visual Classification	Unit Weight (kN/m^3)	Cohesion (kPa)	Friction Angle
Sandy Fill (SW/SP)	SAND, some to trace gravel, trace silt, sub-rounded, very loose, moist, FILL	15.5	0	34^o
Silty Fill (SM/ML)	SAND and SILT, some to trace clay, trace gravel, fragments of hard silt, low to non-plastic, very loose, moist to wet, FILL	15.0	6	32^o
Colluvium (SM)	SAND, silty, trace clay, trace gravel, low to non-plastic, very loose, moist, COLLUVIUM	16.0	0	39^o
Weathered Glaciomarine Silt (ML/CL)	SILT, some sand, some to trace clay, sub-angular sand, low to intermediate plasticity, firm, fissured, sometimes laminated, moist to wet, WEATHERED GLACIOMARINE SEDIMENTS	18.5	0	39^o
Intact Glaciomarine Silt (ML/CL)	SILT, some sand, some to trace clay, sub-angular sand, low to intermediate plasticity, stiff to very stiff, sometimes laminated, moist (often wet at contact w/ overlying unit), INTACT GLACIOMARINE SEDIMENTS	19.0	25	39^o
Glaciomarine Sand (SM/SP)	SAND, some to trace silt, some to trace fine gravel, sub-angular, compact to dense, wet, laminated, GLACIOMARINE SANDS	19.0	0	40^o
Till (SW/SM)	SAND, some to trace silt, some to trace gravel, sub-rounded pebbles, sub-angular sand, very dense, moist, LODGEMENT TILL	21.0	50	40^o

Note: strength parameters obtained from direct shear tests at low (25 to 100 kPa) confining stresses, and from slope stability back analyses

2.2 Phase 1 Investigations

Between late October to mid November of 2005, field inspections were performed at approximately 75 houses along the escarpment as part of the Phase 1 risk assessment. Visual observations by teams of two geotechnical engineers and geoscientists focused on gathering the following information:

- slope angles at the crest of the escarpment;
- evidence of slope deformation at and immediately below the crest of the escarpment;
- nature of the tree cover on the escarpment slope;
- presence and condition of retaining walls, pools and ponds;
- distance of houses to the crest of the escarpment;
- sources of surface drainage directed towards the crest of the escarpment; and,
- representative site photographs.

In addition to the above information, shallow hand auger holes were drilled at the escarpment crest and about 10 m below the crest to assess the thickness of loose fill and loose colluvial soils at each property (Drawing 1). The information obtained in the Phase 1 investigations and risk assessment was used to refine the scope of the second phase of study.

2.3 Phase 2 Investigations

A supplementary CPT and piezometer installation program was initiated following the Phase 1 risk assessment. The principal objective of the new investigations was to better define the soil properties and depth of loose material at the escarpment crest and to provide the instrumentation necessary to monitor the groundwater conditions. Properties investigated along the escarpment were chosen based on results from the initial risk assessment, proximity to previous landslides, and backyard accessibility. They are listed in Table 2.

Table 2. CPT and Piezometer Installation Program Summary

Property	CPT and Electric Piezometer at Crest	Standpipe Piezometer at Crest	Standpipe Piezometer below Crest	Hand-surveyed Cross Section
2377 Berkley	-	√	√	√
2217 Berkley	√	-	√	√
2125 Berkley	-	√	√	√
2480 Hayseed	-	√	√	√
2462 Hayseed	-	√	√	√
Hayseed / Layton Gully	-	√	√	√
1855 Layton	√	-	√	√
1847 Layton	√	-	√	√
2372 Carman	√	-	√	√
2360 Carman	√	-	√	√
2391 Carman	-	√	√	√
1775 Layton	-	√	√	√
1691 Layton	-	√	√	√
2410 Swinburne	√	-	√	√
2402 Swinburne	-	√	√	√
1535 Lennox	√	-	√	√
1425 Lennox	-	√	√	√
1279 Lennox	√	-	√	√

CPT's were carried out and electric piezometers were installed on eight properties near the crest of the escarpment, and standpipe piezometers were installed in hand-auger holes on ten additional properties where access for the CPT rig was not available (Drawing 1). Additionally, standpipe piezometers were installed 10 to 15 m below the escarpment crest at all of the 18 properties that were selected for Phase 2 investigation (Drawing 1). The main purpose of the piezometer installations was to facilitate monitoring of the groundwater conditions with respect to antecedent rainfall, response to intense rainfall conditions, and benefits from the new storm sewer connections.

On some properties, CPT results showed greater fill depths than were obtained through prior hand auger drilling. This is mainly due to the CPT's ability to push through cobble and gravel zones in which a hand auger would otherwise meet refusal. Throughout this program, little groundwater was encountered; in most cases, soils were moist but perched water tables were absent. This suggests that the fill materials are rarely saturated except during periods of very intense and prolonged rainfall.

2.4 Information Provided by Land Owners and DNV

Following the completion of the Phase 1 risk assessment the DNV provided BGC with updated results from drainage inspections and additional geotechnical reports that were on file for properties located along the escarpment. Several property owners also provided useful comments and insight on the history of property development and modification.

New topographic data obtained from a LIDAR survey flown in February 2006 provided an opportunity to generate more precise contour maps (Drawing 1) and a slope map (Drawing 2). Both the new topographic map and slope map more accurately define the escarpment crest and base location, improving the interpreted location of the potential landslides source zones and runout paths. The detailed topographic data also allowed the historic landslide locations to be refined.

Phase 1 and 2 site investigation results and summary data are provided in Appendix I.

3.0 UPDATED BASE-CASE RISK ESTIMATES

New information described in Section 2 was used to update the base-case risk estimates. These estimates represent the unmitigated individual and societal risks along the escarpment following the January 19, 2005 landslide, prior to the implementation of a monitoring program, drainage improvements, property acquisitions, and other remediation undertaken on select properties.

3.1 Updated Landslide Likelihood Estimates

The updated information was used to refine the base-case estimates of landslide likelihood from each potential source area. Significant factors influencing the results included updated DNV drainage reports that provide a more accurate assessment of storm sewer connection status at the time of the January 19, 2005 landslide, and additional hand auger and CPT data that helped to refine the depth of loose material at the crest of the escarpment.

The algorithm developed and calibrated in the Phase 1 risk assessment was used to estimate the updated landslide likelihood from each potential source location relative to the whole escarpment. A landslide frequency of 1 every 4.5 years somewhere along the escarpment is predicted when this algorithm is applied to the most up-to-date information. This landslide frequency is similar to the frequency reported in the Phase 1 risk assessment. Compared to the observed landslide frequency of 1 every 5.5 years, the calculated landslide frequency remains slightly conservative.

Compared to the Phase 1 results, the number of potential landslide source areas with likelihoods greater than two times the escarpment average was reduced from 12 to 11. Thirty-nine potential landslides source areas have failure likelihoods similar to the average for the escarpment, while the remaining 25 potential sources areas have failure likelihoods less than half the average for the escarpment.

Landslide likelihood estimates are tabulated in Appendix II, and are illustrated in Drawing 3.

3.2 Updated Landslide Runout Analysis

Hypothetical landslide runout paths were estimated for each property along the escarpment in the Phase 1 risk assessment. A new LIDAR survey flown in February 2006 provided more accurate topographic data for the Phase 2 assessment. The new survey data allowed the crest of the escarpment to be located more accurately (Drawing 2) and the runout lines along the base of the escarpment to be refined accordingly (Drawing 3). In particular, several landslide initiation zones for the Berkley Road section of the escarpment were repositioned several meters to the east at the revised crest location.

3.3 Updated Consequence Estimation

Spatial probability of impact estimates ($P_{S:H}$) at the base of the escarpment were reassessed using the updated topographic data and our understanding of house locations at the time of the 1972, and 1979, and 2005 landslides. The remaining parameters used to estimate consequences at the crest and base of the escarpment (namely the temporal probability of impact and occupant vulnerability) remained unchanged.

The revised number and position of homes located beneath the historical landslides, and the level of damage they sustained, is shown in Table 3.

Table 3. Damage to Homes Caused by Historical Landslides

Slide Source	Homes >25°	Homes 23 to 25°	Homes 21 to 23°	Homes 19 to 21°
1425 Lennox (1972)	1 – not damaged	2 – not damaged	0	2 – not damaged
2379 Carman (1979)	1 – destroyed	1 – 50% damaged	2 – not damaged	2 – not damaged
2360 Carman (1979)	0	0	1 – not damaged	1 – not damaged
2205 Berkley (1979)	0	0	1 – not damaged	1 – not damaged
2175 Berkley (2005)	1 – destroyed	0	1 – 50% damaged 1 – not damaged	0

Based purely on historical data, the updated spatial probabilities of impact are therefore:

- for homes >25° below escarpment crest, $P_{S:H}$ = 0.667 (2 of 3 destroyed);
- for homes 23 to 25° below escarpment crest, $P_{S:H}$ = 0.167 (0.5 of 3 destroyed);
- for homes 21 to 23° below escarpment crest, $P_{S:H}$ = 0.083 (0.5 of 6 destroyed); and,
- for homes 19 to 21° below escarpment crest, $P_{S:H}$ = 0.0025 (assumed – no data).

3.4 Updated Risk Estimates

As described in the Phase 1 risk assessment report, the general focus for calibrating the risk model to match the historical record was defined as approximately one statistical fatality every 16.5 years. Individual and societal risks were re-calculated using the information gathered during Phase 2 and the updated spatial probabilities of impact defined above. Without calibration the updated risk model would be slightly conservative. To overcome this, the spatial probabilities of impact reported in Section 3.3 were reduced by 20%. The resulting combined risk estimate for the entire escarpment predicts one statistical fatality every 16.9 years, which was deemed to be sufficiently accurate for the purpose of evaluating risk control options.

Supporting calculations for the base-case risk estimates are provided in Appendix II and results are illustrated in Drawing 4. While the total landslide risk is essentially the same as that outlined in the Phase 1 report, the risks estimated for individual properties and landslide source areas have changed in some locations as a result of the new information gathered during the second phase of study. The number of properties where individual risk estimates exceed tolerable criteria defined for existing developments in Hong Kong (an incremental risk of fatality exceeding 10^{-4} per year) decreased from 52 to 43. Of the 43 properties, two are located at the crest of the escarpment while the remainder are located at the bottom of the slope.

Based on comparisons with Hong Kong criteria for societal risk, 20 of the 75 hypothetical landslide source areas along the crest of the escarpment are now estimated to pose unacceptable base-case risk levels and 37 other source areas require further efforts to reduce risks to as low as reasonably practicable (ALARP). In the Phase 1 study, the number of landslide source areas posing unacceptable and ALARP risk levels was 22 and 37, respectively.

4.0 TARGET RISK LEVELS

Quantitative tolerable risk or risk acceptance criteria for landslides have not been defined for British Columbia or DNV.

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. Societal risks imposed by any given landslide hazard are deemed unacceptable if the expected frequency of 1 or more fatalities exceeds 10^{-3} per annum. The Hong Kong Special Administrative Regional Government has adopted, 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.

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

In absence of risk acceptance criteria for DNV, BGC has taken the following approach:

a. risk control options and the framework used to evaluate their associated benefits and costs are described in Section 5 and 6;
b. estimated individual and societal risks following the remedial works undertaken since the January 19, 2005 landslide or that are currently in progress are quantified in Section 7, along with a strategy to reduce the societal risks posed by all remaining source areas exceeding 10^{-3} per year, and individual risks on all remaining properties exceeding 10^{-4} per year; and,
c. additional mitigation options to further reduce the individual risks on all properties to about 10^{-5} per year, or less, are provided in Section 8.

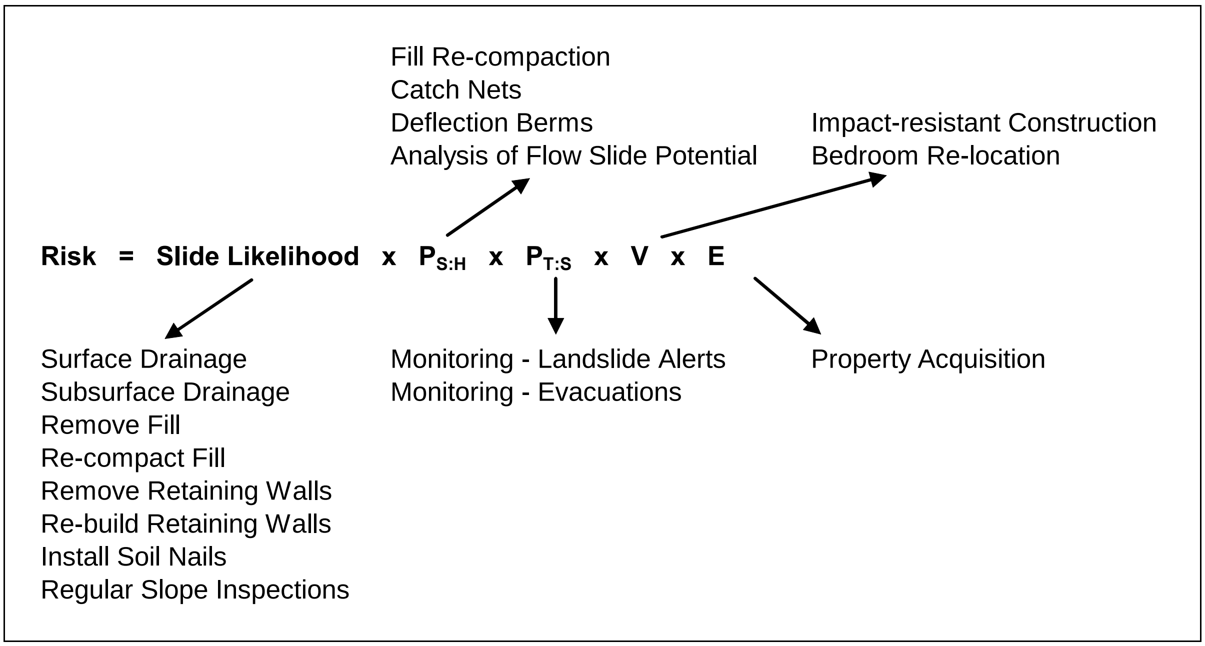
The decision on what risk levels must be tolerated and which remedial options to adopt lies with DNV and the affected residents. This decision should be made giving due consideration to the options available and costs required to achieve each risk level, and with an appreciation for the other risks that should be managed throughout the District.

5.0 RISK CONTROL OPTIONS

5.1 Framework

Figure 1 outlines the equation used in the Phase I risk assessment to estimate the risk of fatality as a result of flow slides originating from the crest of the escarpment. For reference, the terms refer to: the likelihood (annual probability) of slide occurrence; the spatial probability of impact to homes, given the slide occurs ($P_{S:H}$); the occupants' temporal probability of impact ($P_{T:S}$); occupant vulnerability (V); and, the number of occupants (or elements) at risk (E). Reducing the value of any of the terms in the risk equation will reduce the risk of fatality accordingly.

Figure 1. Risk Equation and Options to Reduce Risk of Fatality



The analyses undertaken in the Phase 1 risk assessment were calibrated using historical slide frequency and consequences. The potential for flow slides and the risk of fatality were 'distributed' across the escarpment in a repeatable and transparent manner, and in a way that matched the historical record. The techniques used in Phase 2 to evaluate the potential benefits of the risk control options were consistent with the methodology that was successfully applied in Phase 1.

The framework used to evaluate risk control options involved the following key steps:

- brainstorming to identify potential options to reduce each risk component value (highlighted in Figure 1), followed by a judgement-based assessment of which of the identified options are likely to be viable;
- subjective estimates of the level of risk reduction that could be achieved through the

application of each option. For many of the options, the landslide probability algorithm outlined in Table 4 was used to systematically quantify the level of risk reduction; and,

- development of generic designs and quantities estimates for the most promising options. These were discussed with local contractors to obtain their input on constructability and cost.

5.2 Viable Risk Control Options

Not all of the options identified in Figure 1 are considered practical to implement. Furthermore, some options could be implemented at isolated locations, while it is recommended that others be implemented across the entire escarpment or in tandem with other options if the full benefits are to be realized. A brief description of the risk control options is provided below, along with an indication of which were chosen for further evaluation. Schematic illustrations highlighting key aspects of several of the options are provided in Appendix III.

Options to Reduce Slide Likelihood

Flow slides can occur when shear stresses exceed shear strengths in loose, saturated soils, causing them to deform and collapse which leads to a further reduction in shear strength. Options to reduce the likelihood of future flow slides originating from near the crest of the escarpment involve increasing the shear strength, decreasing the shear stress, reducing the soil collapse potential, or reducing the volume of potentially unstable soil. Means to accomplish this include:

- **Surface Drainage** – including connecting homes to the storm sewer system and improving roadway storm water management. Storm water management presents one of the most promising ways to reduce landslide risk. It should be carried out with ongoing maintenance and inspections to ensure that the systems continue to function as intended.
- **Subsurface Drainage** – including construction of trench drains, installation of horizontal drains, or installation of springhead drains. Site access and escarpment stratigraphy generally make installation of horizontal drains impractical. In most cases, unless carried out in conjunction with other options such as fill removal or compaction, subsurface drainage is expected to be more costly and less beneficial than surface drainage improvements. Exceptions include installation of shallow subsurface drains at locations of known seepage below the crest of the escarpment. This is best carried out using shallow, gravel-filled trenches lined with geotextile, referred to as springhead drains (e.g. Shannon and Wilson, 2000). Steel or HDPE piping will be required to convey the water down slope so that it can be discharged in a safe location. Ongoing maintenance and inspections will be required to ensure the systems continue to perform as intended.

- **Fill Removal** – including excavation and removal of loose fill materials within reach of the escarpment crest. Erosion control and bioengineering measures will also be required to maximize the benefits of fill removal. Ongoing inspection will be required to ensure the slope continues to perform as intended.
- **Retaining Wall Removal** – including excavation and/or compaction of fills, where walls are not essential and where they are in a state of disrepair. Erosion control and bioengineering measures will also be required to maximize the benefits of retaining wall removal. Ongoing inspection will be required to ensure the slope continues to perform as intended.
- **Fill Compaction** – including temporary excavation and re-compaction of loose fill and colluvial soils. This provides a means of improving soil strength and reducing water infiltration potential, thereby reducing the potential for flow slides. It may also reduce slide runout potential. Erosion control and bioengineering measures will be required to maximize the benefits of fill compaction. Ongoing inspection will be required to ensure the slope continues to perform as intended. Fill compaction is best-suited for locations where it is not practical to excavate and remove all loose soils from the top of the slope segment.
- **Retaining Wall Reconstruction** – where walls are necessary to maintain the stability of house foundations, and where walls are currently in a state of disrepair. Walls would require provisions for sub-drainage, and would need to be designed to accommodate the latest earthquake loads specified in building codes. Though some residents may choose to reconstruct retaining walls, at this point in time wall reconstruction appears to be costly and non-essential, and has not been evaluated in further detail.
- **Soil Nail Wall Installation** – including the installation of driven or grouted steel bars and reinforced shotcrete on steep slopes where fill removal or compaction is not practical. Walls would require provisions for sub-drainage. At this point in time soil nail wall installation appears to be costly and non-essential, and has not been evaluated in further detail.
- **Slope Inspections** – to identify changed (worsening) conditions that can be mitigated before they lead to slope failure. As indicated above, inspections will be required for all options to ensure that the works continue to perform as intended. Therefore, benefits and costs of incorporating inspections in the overall risk management program have been included in the evaluation of each of the viable risk control options.

<u>Options to Reduce Spatial Probability of Impact</u>

Spatial probability of impact is related to the anticipated landslide runout potential. Two options were identified to reduce runout potential:

- **Debris Flow Barriers** – flexible barriers such as those used to protect against rock fall and debris flow, provide a means of decreasing slide travel distance. These have been used to successfully stop rapid debris flows up to several hundred cubic metres in volume. They have a relatively small construction footprint and may warrant further consideration below some locations where houses are located in close proximity to the toe of the slope and where it is not practical to remove or compact all fill materials. They could also provide some measure of protection against potential mid-slope failures.

- **Deflection Berms** – earth berms to deflect potential slide debris away from densely occupied areas. These tend to require a large footprint on relatively gentle slopes for construction. Since homes tend to be constructed close to the base of the escarpment along most of its length, deflection berms do not appear practical and have not been considered further.

Use of debris flow barriers will potentially raise concerns over ownership, maintenance responsibility, and the risks they might impose on the public. For example, children might climb on the barriers and expose themselves to risk of injury. These ‘costs’ will need to be weighed carefully before a final decision to proceed with barrier construction is made.

Options to Reduce Temporal Probability of Impact

The temporal probability of impact can be reduced by reducing the time residents are exposed to landslide hazards when the potential for landslides is elevated. This can be achieved by monitoring rainfall and groundwater conditions using the system developed and implemented in late 2004, and issuing voluntary or mandatory evacuation alerts when pre-set thresholds are exceeded. However, this option does not appear viable or necessary in the long-term. It is simply not possible to live a ‘normal’ life in a zone subject to evacuations on a recurring basis. Furthermore, it is possible to dramatically reduce the risk of fatality (and property damage) caused by landslides along the Berkley Escarpment by removing loose fill and improving drainage as outlined in a staged remediation plan provided in the sections that follow. Once these measures are implemented the need to operate the monitoring system for the purpose of triggering evacuations or landslide advisories should no longer be required.

Consequently, BGC recommends that the monitoring system be operated as follows:

- prior to completion of Stage 1 Remediation – voluntary evacuation alerts are to be issued to residents exposed to an individual risk greater than 10^{-4} per year when pre-determined thresholds are exceeded; landslide advisories are issued to remaining residents at the top and base of the Berkley Escarpment; and,

- following Stage 1 and prior to completion of Stage 2 Remediation – landslide advisories are issued to all residents at the top and base of the Berkley Escarpment when pre-determined thresholds are exceeded.

Evacuation alerts would contain a recommendation to seek alternate accommodations until such time as rainfall has subsided and groundwater conditions have improved; landslide advisories would only contain a recommendation to avoid recreational trails that cross steep slopes.

Once Stage 2 Remediation is complete, BGC recommends the system operate solely for the purpose of monitoring the ongoing performance of the drainage improvements and, if desired, for the purpose of issuing regional landslide advisories to users of recreational trails throughout the District. No further evaluation has been carried out to assess the direct benefits of long-term rainfall and groundwater monitoring.

Options to Reduce Vulnerability

There are ways to reduce the vulnerability of house occupants in the case that their home is struck by landslide debris. Two examples include:

- **Impact-Resistant House Wall Construction** – such as construction using reinforced concrete; and
- **Re-Location of Bedrooms** – since most people spend more time in their bedrooms than elsewhere in their homes. Positioning bedrooms above the ground floor and as far from the toe of the slope as possible would minimise the potential for loss of life.

At this point, neither option appears practical or necessary. No further evaluation of their costs and benefits has been undertaken.

Options to Reduce Number of People at Risk

Eight properties have been purchased by the DNV with Provincial assistance, the homes have been vacated, and they are in the process of being demolished. Some of the properties may be converted to parkland; others will likely be suitable for redevelopment once remedial works in the vicinity of the January 19, 2005 landslide have been completed.

Property acquisition and house demolition effectively reduces the number of people at risk of fatality to zero; however, future property acquisitions are not being considered by the District. Furthermore, it appears that risks of fatality from landslides can be reduced to levels less than those faced in everyday life by other more practical means, as demonstrated by the cost-benefit analyses reported in Section 6.

6.0 COST – BENEFIT ANALYSIS

Benefits and costs have been estimated for each viable option identified above.

Benefits are measured in terms of the potential reduction in the risk of fatality. For a given risk control option, this will vary across the escarpment depending on the current potential for landslides at each location and the position and number of homes exposed to each particular landslide hazard. For the purpose of illustrating potential benefits, risk reduction is quantified for the following typical scenario:

- prior to mitigation, the hypothetical P_{slide} = 0.0024 (average conditions);
- the hypothetical slide source area currently has conditions that would lead to attribute scores of 1.0 for each of the attributes considered in the P_{slide} algorithm, as shown in Table 4;
- the nearest home at the crest of the escarpment is located within 9 m of the escarpment crest; and,
- one home is located within each of the slide runout zones (i.e. >25^o, 23 to 25^o, 21 to 23^o, and 19 to 21^o) within the hypothetical slide path.

The societal risk for this typical scenario is $1.0x10^{-3}$ fatalities per year, or approximately $3.1x10^{-2}$ fatalities for a 30 year period of exposure to the unmitigated landslide hazard.

Each viable risk control option has an associated cost, usually including a capital cost for construction (including engineering costs) and an operating cost for ongoing inspections and maintenance. Typical capital and annual operating costs have been estimated for each option, as illustrated in Appendix III. The net present value (NPV) of the combined total costs has also been estimated for a 30 year period, based on an assumed 5% discount rate.

Lastly, the cost-benefit ratio is calculated according to:

- Cost-Benefit Ratio = (NPV of 30 Year Cost) / (30 x [unmitigated risk – mitigated risk]).

In general, risk control options with low cost-benefit ratios provided the greatest level of risk reduction for each dollar spent; however, this ratio will vary from property to property depending on the site-specific conditions. Thus, the cost-benefit ratios provide a useful guide but should not be taken too literally.

In Sections 7 and 8 we describe possible risk control strategies, including their estimated costs and benefits. The benefits described in those sections account for the site-specific conditions at each property.

6.1 Options to Reduce Probability of Flow Slides

A simple algorithm was developed to assign a likelihood of flow slides to each segment of the escarpment crest using site observations gathered during the Phase 1 assessment. The algorithm took the form of:

- $P_{slide(site)}$ = [slope score] x [loose soil score] x [water score] x [deformation score] x [$P_{slide(avg)}$],

where slope, loose soil, water, and deformation scores were assigned as shown in Table 4. The original landslide likelihood algorithm has been modified slightly to account for the potential benefits of the various risk control options. The scores have been calibrated such that, hypothetically, the 'best possible' segment would have a 1:10,000 annual probability of generating a flow slide from the escarpment crest. BGC subjectively estimates this failure frequency is similar to or less than what existed prior to slope development. This assessment is based on the assumption that fills will be removed, final slope angles will be equivalent or less than they were in their natural state, and that surface water that would naturally flow over the escarpment crest will be captured and directed into the storm sewer system.

It is important to reiterate that flow slides with significant damage potential are a type of very rapid landslide with long runout potential and require an initial volume of saturated debris that usually exceeds several tens of cubic metres. Small slumps and debris slides with limited runout potential are expected to occur in colluvial soils along the natural escarpment, but these are expected to have a lower potential to cause fatalities and have not been included in the risk assessment at this point in time.

Table 4. Flow Slide Likelihood Algorithm

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 As above, and sub-drains installed below crest where seepage observed = 0.35 Runoff from backyard = 0.5 Plus half roof = 0.75 Plus full roof = 1.0 Plus driveway = 1.25 Plus 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 $P_{slide(avg)}$ = 0.0024 $P_{slide(max)}$ = 0.024 $P_{slide(min)}$ = 0.0001

In the sub-sections that follow, the way that each potential risk control option is anticipated to reduce the likelihood of flow slides is described and the estimated typical costs and benefits of implementing each option are presented. Calculations are tabulated in Appendix III.

Surface Drainage

We understand surface drainage improvements are underway and the intent is that all homes at the crest of the escarpment will be connected to the storm sewer system before the onset of the 2006/07 rainy season.

When all properties adjacent to a segment of the escarpment crest are connected to the storm sewer system, and when roadway storm water drainage is managed, the 'Water Score' in Table 4 is reduced to a value of 0.35. For the typical escarpment segment, P_{slide} is reduced to 8.4×10^{-4} per year. For the typical risk scenario, societal risk is expected to be reduced by 65% to a value of 3.6×10^{-4} per year.

Over time, improvements to surface drainage may stabilize slopes to the point that deformation abates. At some properties, this could potentially reduce the 'Deformation Score' to a value of 0.5, resulting in a further level of risk reduction. This has not been accounted for at this time in the cost-benefit analysis, but could be at a later date if ongoing inspections demonstrate that slope deformation is no longer active.

Connection to the storm sewer system is estimated to cost $9,000, on average. Operation and maintenance costs, including a technical inspection every five years, are expected to amount to $350 per year, on average. The NPV of this option is about $14,500, per slope segment.

The cost-benefit ratio for this option is $712,000 per statistical life saved, when the costs and benefits are considered over a 30 year timeframe.

Subsurface Drainage

Seepage was identified below the escarpment crest at about 10 of the 75 slope segments. Installation of subsurface drainage improvement, or springhead drains, might be warranted at some of these locations where the risk to down slope residents exceeds tolerable levels.

In addition to connecting homes to the storm sewer system, subsurface drainage measures will be required at locations where seepage points are identified during fill removal in order to reduce the 'Water Score' in Table 4 to a value of 0.35. For the typical escarpment segment, P_{slide} is reduced to 8.4×10^{-4} per year. For the typical risk scenario, societal risk is expected to be reduced by 65% to a value of 3.6×10^{-4} per year.

The NPV of the surface drainage improvements is $14,500. Additional capital costs for installation of subdrains and piping to convey water to the base of the escarpment are estimated at $5,500. Additional maintenance and inspection costs for the subdrains are estimated at $350 per year. The incremental NPV of subdrains is $11,000, giving a total NPV of about $25,500 for both surface drainage improvements and installation of subdrains at known seepage points.

The cost-benefit ratio for this combined option is $1,251,000 per statistical life saved, when the costs and benefits are considered over a 30 year timeframe.

Fill Removal

About 12 of the 75 slope segments lack retaining walls, yet have more than 2 m of fill and loose colluvial soil located at the crest of the escarpment. Fill removal might be warranted at some of these locations where the risk to down slope residents exceeds tolerable levels.

When the thickness of loose soil at the crest and within 10 m of the crest of the escarpment is reduced to the less than 1 m and less than 2 m, respectively, the ‘Loose Soil Score’ in Table 4 is reduced to a value of 0.35. Furthermore, the slope angle at the crest of the escarpment can typically be reduced to less than 35^o in the process, resulting in a ‘Slope Score’ of 0.8. For the typical escarpment segment, P_{slide} is reduced to $6.7x10^{-4}$ per year. For the typical risk scenario, societal risk is expected to be reduced by 72% to a value of $2.9x10^{-4}$ per year.

Fill excavation, disposal, and subsequent erosion control is estimated to cost about $30,000, on average. Operation and maintenance costs, including a technical inspection every five years, are expected to amount to $50 per year, on average. The NPV of this option is about $31,000 per slope segment.

The cost-benefit ratio for this option is $1,352,000 per statistical life saved, when the costs and benefits are considered over a 30 year timeframe.

Retaining Wall Removal

About 17 of the 75 slope segments contain retaining walls that support more than 2 m of fill at the crest of the escarpment. Ten of these walls show evidence of deformation. Fill and retaining wall removal might be warranted at some of these locations where the risk to down slope residents exceeds tolerable levels.

When the thickness of loose soil at the crest and within 10 m of the crest of the escarpment is reduced to the less than 1 m and less than 2 m, respectively, the ‘Loose Soil Score’ in Table 4 is reduced to a value of 0.35. Furthermore, the slope angle at the crest of the escarpment can typically be reduced to less than 35^o in the process, resulting in a ‘Slope Score’ of 0.8. For the typical escarpment segment, P_{slide} is reduced to $6.7x10^{-4}$ per year. For the typical risk scenario, societal risk is expected to be reduced by 72% to a value of $2.9x10^{-4}$ per year.

Wall removal, fill excavation, disposal, and subsequent erosion control is estimated to cost $45,000, on average. Operation and maintenance costs, including a technical inspection every five years, are expected to amount to $50 per year, on average. The NPV of this option is $46,000 per slope segment.

The cost-benefit ratio for this option is $2,021,000 per statistical life saved, when the costs and benefits are considered over a 30 year timeframe.

Fill Compaction

About 40 of the 75 slope segments contain between 1 and 2 m of fill at the crest of the escarpment, and about half of these show some evidence of deformation. Fill compaction might present a viable alternative to fill or retaining wall removal at some of these locations where the risk to down slope residents exceeds tolerable levels. In other locations where the fill thickness is greater, geometric constraints may not permit all fill to be removed from site. Temporary excavation and re-compaction of the fill left on site might be warranted in order to achieve the greatest possible level of risk reduction. In both cases, provision for drainage at the base of the re-compacted soils is recommended.

Like for fill removal, the benefits of compaction are accounted for by reducing the thickness of loose soil. When the thickness of loose soil at the crest and within 10 m of the crest of the escarpment is reduced to the less than 1 m and less than 2 m, respectively, the 'Loose Soil Score' in Table 4 is reduced to a value of 0.35. Furthermore, it is anticipated the slope angle at the crest of the escarpment can typically be reduced to less than 35^o in the process, resulting in a 'Slope Score' of 0.8. For the typical escarpment segment, P_{slide} is reduced to 6.7×10^{-4} per year. For the typical risk scenario, societal risk is expected to be reduced by 72% to a value of 2.9×10^{-4} per year.

Fill compaction may improve stability to the point that deformation abates, reducing the 'Deformation Score'. For the purpose of cost-benefit analysis, the possible reduction in the 'Deformation Score' has been ignored.

Site access, clearing and grubbing, temporary excavation and fill re-compaction, and subsequent erosion control is estimated to cost $48,000, on average. Operation and maintenance costs, including a technical inspection every five years, are expected to amount to $350 per year, on average. The NPV of this option is $53,000 per slope segment.

The cost-benefit ratio for this option is $2,361,000 per statistical life saved, when the costs and benefits are considered over a 30 year timeframe.

In some cases, both fill re-compaction and fill or retaining wall removal may be required. In these cases, an incremental capital cost of $23,000 has been added to account for fill re-compaction and provision of drainage measures.

6.2 Options to Reduce Spatial Probability of Impact

The implementation of drainage improvements, in conjunction with fill and retaining wall removal and fill compaction, as outlined in Section 6.1, is expected to significantly reduce the likelihood of future flow slides initiating from the crest of the escarpment. Depending on the level of tolerable risk that is adopted, however, additional risk control measures may be required. This need might also arise where natural geological conditions and geometric constraints on fill removal do not permit slope angles to be reduced to less than 35^o. The potential costs and benefits of installing flexible debris flow barriers near the base of the escarpment as a means of further reducing risk levels are discussed below.

The Phase 1 risk assessment used the angle from a given house location to the crest of the escarpment as a means of estimating the spatial probability of impact. Recently acquired topographic data and house information have lead to revised spatial probability of impact estimates, as shown in Table 5. Table 5 has been modified to illustrate the potential benefits of installing flexible debris flow barriers up slope of houses at the base of the escarpment. Flexible barriers such as these can be designed to stop rapid debris flows up to 1000 m^3 in volume without sustaining significant damage (Geobrugg 2004). Their ability to capture larger events remains unproven and is a source of uncertainty for their application along the Berkley Escarpment.

Table 5. Spatial Probability of Impact with and without Debris Flow Barriers

Angle from House to Landslide Initiation Zone	Spatial Probability of Impact Leading to Damage $P_{S:H}$	Spatial Probability of Impact Following Barrier Installation $P_{S:H}$
> 25^o	0.534	0.267
23^o to 25^o	0.134	0.067
21^o to 23^o	0.066	0.033
19^o to 21^o	0.002	0.001

As outlined in Table 5, it has been estimated that installation of debris flow barriers could reduce the probability of spatial impact, and consequently, the risk of fatality, by about 50% over unmitigated values. For the typical risk scenario, societal risk is expected to be reduced to a value of $5.3x10^{-4}$ per year.

Catch net design, materials and installation is estimated to cost $75,000, on average, to protect against each potential slide source area. Operation and maintenance costs, including a technical inspection every five years, are expected to amount to $150 per year, on average. Maintenance would mainly involve clearing of fallen trees. The NPV of this option is $77,500 per slope segment.

The cost-benefit ratio for this option is $5,020,000 per statistical life saved, when the costs and benefits are considered over a 30 year timeframe. This is considerably higher than the cost-benefit ratios estimated for drainage improvements and fill removal as outlined above. Thus, installation of debris flow barriers should be considered as a last resort where evidence of active deformation up slope continues to persist despite the implementation of the other remedial works.

6.3 Options to Reduce Number of People at Risk

Property acquisition and house demolition is one means of reducing the number of people potentially at risk. The costs, including property acquisition, demolition, and long-term maintenance, are estimated at $760,000 per property. Estimated benefits consider the reduction in risk of fatality assuming four occupants of a home located >25^{o} below the crest of the escarpment re-locate to an area where they are exposed to 'zero' risk from landslides or other hazards. In this case, the societal risk is reduced by approximately 72% to $2.9x10^{-4}$ per year for the hypothetical landslide likelihood scenario described above.

The cost-benefit ratio for property acquisition is approximately $34,500,000 per statistical life saved, when the costs and benefits are considered over a 30 year timeframe. The results suggest that the marginal costs of risk reduction achieved through means of property acquisition are disproportional and it appears that further property acquisitions cannot be justified on the basis of cost-benefit analysis.

7.0 STRATEGY TO REDUCE INDIVIDUAL RISK TO <10^{-4} PER YEAR

A risk of 10^{-4} per year is roughly equivalent to the average Canadian's annual risk of fatality in a motor vehicle accident (Statistics Canada 2005). It is also the maximum tolerable risk recommended for existing developments exposed to landslide hazards in Hong Kong and Australia. Furthermore, these jurisdictions demand that the societal risk posed by any one landslide hazard is less than 10^{-3} per year. DNV might consider adopting an interim level of tolerable risk that meets or exceeds these criteria.

Consequently, outlined below is a strategy to reduce the individual risk on all properties to less than 10^{-4} per year, and the societal risk from all potential slide source areas to less than 10^{-3} per year. This is referred to as Stage 1 Remediation. It begins by describing the estimated risk reduction from the base-case estimates arising from risk control actions that have already been undertaken or are currently underway. These include implementation of the storm water drainage improvements, acquisition of properties for purposes of remediation, and removal of a retaining wall and fill at one potential slide source area. Once these improvements are accounted for, recommendations are provided to address the unacceptable risks posed by the remaining landslide source areas.

7.1 Storm Sewer Connections and Storm Water Management

DNV is in the process of ensuring that all properties at the crest of the escarpment are connected to the storm sewer system. This, in conjunction with improved roadway storm water management and ongoing inspections, will have a significant impact on the potential for future slides.

Storm sewer connections and roadway drainage improvements are expected to reduce the total annual probability of flow slides by about 65%, from 2.2×10^{-1} per year to 7.5×10^{-2} per year. They are expected to reduce the risk of fatality along the escarpment from 5.9×10^{-2} per year to 2.2×10^{-2} per year.

Approximately 43 properties required connection to the storm sewers following the January 19, 2005 landslide, at an estimated average capital cost of $9,000, for a total cost of $387,000. It is anticipated that up to 12 of these properties will require subsurface drainage measures to control seepage from below the crest of the escarpment, at an estimated average capital cost of $5,500, for a total additional cost of $66,000.

7.2 Retaining Wall and Fill Removal at 1593 Lennox

Cracks developed in fill behind by a series of timber retaining walls on the west side of 1593 Lennox. This was the highest rated site, in terms of societal risk, as determined during the Phase 1 risk assessment.

DNV has removed the fill and retaining wall, reducing the slope angle near the crest of the escarpment in the process. The roof and driveway have been connected to the storm sewer system, and roadway curbs should be inspected to ensure storm runoff is directed into the sewer.

The improvements at 1593 Lennox are expected to reduce the total annual probability of flow slides by an additional 10%, from $7.5x10^{-2}$ per year to $6.8x10^{-2}$ per year. They are expected to reduce the risk of fatality along the escarpment from $2.2x10^{-2}$ per year to $2.0x10^{-2}$ per year.

7.3 Fill Removal and Compaction at 2157, 2175, 2191, and 2205 Berkley

Four properties at the crest of the escarpment were purchased by the DNV with Provincial assistance: 2157, 2175, 2191, and 2205 Berkley. Design work is underway to demolish some or all of the homes on these properties, to improve surface drainage, pull back fill materials, compact underlying loose colluvial soils, and re-vegetate the slope.

The improvements at these properties are expected to reduce the total annual probability of flow slides by an additional 9%, from $6.8x10^{-2}$ per year to $6.1x10^{-2}$ per year. They are expected to reduce the risk of fatality along the escarpment from $2.0x10^{-2}$ per year to $1.8x10^{-2}$ per year.

7.4 Permanent Sterilization of 2175 Berkley and 2440 Chapman Way

In addition to the four properties at the crest of the escarpment, four properties along the base were also purchased by the DNV with Provincial assistance: 2274, 2290, and 2440 Chapman Way, and 2318 Treetop Lane.

Theoretically, once remedial measures at the crest of the escarpment are complete, re-occupation of most of these properties would present levels of individual risk less than 10^{-5} per year, which is the risk tolerated in Hong Kong for new development on slopes. However, DNV have indicated they are unlikely to re-develop 2175 Berkley or 2440 Chapman Way.

Permanent sterilization of these properties has a limited impact on the total risk of fatality for the overall escarpment, which remains at $1.8x10^{-2}$ per year.

Projected risk estimates upon completion of the works in progress are tabulated in Appendix IV.

7.5 Remaining Source Areas Leading to Individual Risk Levels >10^{-4}

Following completion of the remedial works outlined above, only the following five landslide source areas will continue to present societal risks greater than 10^{-3} per year and / or to place occupants of homes at the base of the escarpment at individual risk levels exceeding 10^{-4} per year (Drawing 5):

- 1425 Lennox;
- 2402 Swinburne;

- 2379 Carman;
- Hayseed/Layton Gully; and,
- 2462 Hayseed.

The following additional remedial works at the top of the escarpment are recommended to reduce the risks posed by these landslide source areas:

1425 Lennox

- Remove retaining wall, pullback all fill located within 10 m of the crest of the escarpment, compact any remaining loose soils, and re-vegetate the new slope at an approximate capital cost of $70,000.

2402 Swinburne

- Remove retaining wall, pullback all fill located within 10 m of the crest of the escarpment, compact any remaining loose soils, and re-vegetate the new slope at an approximate capital cost of $70,000.

2379 Carman

- Pullback all fill located within 10 m of the crest of the escarpment, compact any remaining loose soils, and re-vegetate the new slope at an approximate capital cost of $53,000.

Hayseed/Layton Gully

- Pullback all fill located within 10 m of the crest of the escarpment and re-vegetate the new slope at an approximate capital cost of $30,000.
- Install sub-drains near the escarpment crest and control seepage flow to the base of the escarpment in anchored drain pipes at an approximate capital cost of $5,500.

2462 Hayseed

- Pullback all fill located within 10 m of the crest of the escarpment, remove a series of low retaining walls, compact any remaining loose soils, and re-vegetate the new slope at an approximate capital cost of $70,000.

The total order-of-magnitude cost for this additional work is estimated at $300,000.

The additional improvements at these properties are expected to reduce the total annual probability of flow slides by an additional 20%, from 6.1×10^{-2} per year to 5.0×10^{-2} per year. They are expected to reduce the risk of fatality along the escarpment from 1.8×10^{-2} per year to 1.1×10^{-2} per year. The individual risks faced by occupants of all properties at the crest and base of the escarpment will be reduced to less than 10^{-4} per year as shown on Drawing 6.

Projected risk estimates upon completion of the additional works recommended here are tabulated in Appendix V.

8.0 OPTIONS TO REDUCE INDIVIDUAL RISK TO <10^{-5} PER YEAR

Once the benefits for the remedial work outlined in Section 7 are accounted for, 34 landslide source areas are expected to continue to place homes at the base of the escarpment at individual risk levels exceeding 10^{-5} per year. This includes five source areas where work will have already been undertaken, all of which currently show evidence of active slope deformation in soils located down slope of what can easily be reached by an excavator and which have homes located at angles >25^{o} directly below them:

- 1425 Lennox;
- 2402 Swinburne;
- 2379 Carman;
- Hayseed/Layton Gully; and,
- 2462 Hayseed.

If ongoing inspection shows that the remedial works prescribed above have caused slope deformations to abate, estimated risks will be reduce further to a value of approximately 10^{-5} per year. If not, additional measures such as the installation of flexible debris flow barriers down slope may be warranted.

When the risk estimates are reported to one significant digit, the following 29 additional source areas will continue to place down slope home occupants at risks exceeding 10^{-5} per year:

Table 6. Additional Source Areas Posing >10^{-5} Risk Following Phase 1 Mitigation

Source Areas Above Homes Located >25° from Crest of Escarpment	Source Areas Above Homes Located <25° from Crest of Escarpment
1477 Lennox – wall; moderate access	1383 Lennox – wall; poor access
2391 Carman – wall; moderate access	1479 Lennox – wall; moderate access
2360 Carman (south) – no wall; poor access	**1491 Lennox** – wall; poor access
2360 Carman (north) – no wall; moderate access	**1535 Lennox** – wall; poor access
2372 Carman – no wall; good access	**1557 Lennox** – wall; poor access
2386 Carman – no wall; good access	**1583 Lennox** – wall; poor access
1839 Layton – no wall; good access	**2410 Swinburne** – no wall; moderate access
1847 Layton – no wall; good access	**1691 Layton** – no wall; good access
1855 Layton – no wall; good access	**1709 Layton** – no wall; good access
1863 Layton – no wall; good access	1739 Layton – no wall; moderate access
2448 Hayseed – wall; moderate access	1815 Layton – wall; moderate access
2454 Hayseed – wall; good access	**2217 Berkley – no wall; good access**
2474 Hayseed – wall; poor access	
2480 Hayseed – wall; poor access	
2486 Hayseed – wall; moderate access	
2125 Berkley – wall; good access	
2141 Berkley – wall; poor access	

Notes:

1. Some source areas not included in Table 6 have limited fill and show no evidence of instability, yet will continue to pose risk to individuals as high as 1.2×10^{-5} after the mitigation proposed in Section 7 is carried out. This is considered to be within the margin of error for the risk assessment process and additional slope stabilization at these properties is not considered practical.
2. Source areas shown in **bold** text show evidence of slope deformation below the escarpment crest (including slides, leaning trees, or bulging retaining walls) or have thick fills below the crest of the escarpment.

The simplest way to further reduce the risks from the potential slide source areas listed above is to remove retaining walls (where present) and loose soils from the crest of the escarpment. Where access is poor, geometric constraints between the homes and the crest of the escarpment may not permit all loose materials to be removed. In these cases, re-compaction of the remaining loose soils may be required. Accordingly, the following works could be carried out as part of Stage 2 Remediation:

- Remove retaining walls and fills (8 source areas) at an estimated capital cost of $360,000;
- Remove retaining walls and fills, compact remaining soils (8 source areas) at an estimated capital cost of $560,000;
- Remove fills (12 source areas) at an estimated capital cost of $360,000; and,
- Remove fills and compact remaining soils (1 source area) at an estimated capital cost of $53,000.

The total order-of-magnitude cost for this additional work is estimated at $1,340,000. The completion of all works outlined about is recommended; however, the scheduling of, and level of resources allocated to, mitigation work should be prioritised based on an assessment of the resources available to carry out similar works throughout the District at other locations where the risks to individuals are the same or higher.

If the works are to be further prioritised and carried out in stages, the source areas situated above homes that are at an angle >25^o from the escarpment crest, and that show evidence of instability or contain thick fills, should be addressed first. These are highlighted in bold text in the first column of Table 6. All remaining source areas listed in the first column of Table 6, plus the source areas listed in bold in the second column of the Table are of the next highest priority. The remaining source areas in the second column of Table 6 are of lowest priority.

Projected risk estimates upon completion of the additional works listed above are tabulated in Appendix VI.

Once the benefits for the remedial work outlined above are accounted for, four of the landslide source areas listed in Table 6 are expected to continue to place homes at the base of the escarpment at individual risk levels slightly exceeding 10^{-5} per year:

- 2360 Carman (south)
- 2372 Carman
- 1863 Layton
- 2448 Hayseed

Like the other five source areas described at the beginning of Section 8, these currently show evidence of active slope deformation in soils located down slope of what can easily be reached by an excavator and have homes located at angles >25^o directly below them. If ongoing inspection shows that the remedial works listed above have caused deformations to abate, estimated risks will be reduce further to a value of approximately 10^{-5} per year. If not, additional measures such as the installation of flexible debris flow barriers down slope may be warranted.

If deemed necessary, the installation of flexible debris flow barriers above the homes beneath these nine source areas, in conjunction with the works identified above, could reduce estimated individual risks to about 10^{-5} per year, regardless of whether or not slope deformations abate. The total capital cost to install these barriers is estimated at $675,000. If desired, this could be carried out as the final stage of remediation, possibly following an assessment of the performance of measures undertaken during the earlier stages of mitigation, and following a more detailed assessment of the residual risks posed by potential mid-slope failures. Potential debris flow barrier locations are illustrated on Drawing 7.

9.0 RECOMMENDATIONS FOR FINAL DESIGN AND CONSTRUCTION

In order to implement the risk control options described above, detailed site investigation and final engineering design will usually be required to 'field fit' the option to the local site conditions. Schematic illustrations of risk control options are presented in Appendix III that shows the basic concepts and details that require final design.

Design and implementation of the surface drainage options including connecting homes to the storm sewer system and improving roadway storm water management is not illustrated in Appendix III. We understand the design and construction of works to connect homes to the storm sewer system is well underway. Further work is required to ensure that all properties containing level driveways, or driveways that slope towards the escarpment crest, are fitted with a curb to prevent roadway drainage from flowing towards the slope. Nominally, these curbs should be at least 10 cm higher than the roadway pavement surface.

A schematic illustration of subsurface drainage in Appendix III provides key design concepts required for the installation of springhead drains. Springhead drains capture and control seepage zones located along the escarpment. Seepage is collected by the geotextile lined gravel-filled drains and flows down a steel or HDPE pipe discharging in a safe location beyond the base of the slope. Alternatively, water could be collected and pumped up slope into the storm sewer system. This may not be practical where seepage zones are situated well below the crest of the escarpment. The design of the drains and required piping must account for anticipated seepage inflows, be monitored and periodically maintained. Given the steep slopes and varied terrain along the escarpment the discharging pipe should be well anchored and capable of accommodating some deformation.

Fill removal in conjunction with erosion control and re-vegetation of the slope is recommended at many locations. If possible the finished graded slope should be reduced to a horizontal to vertical ratio of 2:1 (26.7°). Bioengineering erosion control measures are recommended to help maintain the long-term stability of the slope – these should be designed and installed by qualified professionals.

In some cases removal of all loose material from the top of the slope may not be practical. For this reason a fill compaction option is included in Appendix III. This option involves temporarily excavating individual trenches parallel to the slope, placing a granular underdrain, then backfilling each trench by re-compacting the excavated soils in 150 mm lifts using small equipment. Re-compacting the fill will reduce water infiltration potential and increase soil strength, thereby reducing the potential for flow slides. As with fill removal, fill compaction requires that erosion control and slope re-vegetation be carried out to be most effective.

Prior to construction of any remediation measures the final design should be reviewed by an independent geotechnical engineer to ensure the design will achieve the required level of risk reduction.

The 'design engineer' should be present on site or make regular site inspections during construction to ensure ground conditions are as anticipated, to modify the design if necessary, and to prepare 'as built' drawings and a completion report that should be provided to DNV and the property owner.

10.0 RECOMMENDATIONS FOR MONITORING, MAINTENANCE AND INSPECTION

Regular monitoring, inspections and maintenance of remedial measures are critical to demonstrate that the implemented remedial works improve slope stability and cause deformations to abate, and to ensure that the measures continue to perform as intended. If deformation, seepage, erosion or the placement of fill is observed along the escarpment during a visual inspection, further remedial measures should be undertaken. Inspections may also be used to identify locations where lawn cuttings or other debris is being placed at the crest of the escarpment. These inspections should be carried out by property owners on an annual basis, and following very heavy rainfall events. An inspection carried out by qualified geotechnical personnel should be carried out at least once every five years. In order to improve inspection efficiency and preserve documentation of the results, use of a database to record visual inspection observations should be considered. The total annual cost of completing technical inspections along the crest of the escarpment is estimated at approximately $15,000.

Regular inspections of the drainage systems along the escarpment are required to ensure drainage functionality. Efficient and effective drainage systems are critical aspects of the risk control for the escarpment. Therefore we suggest DNV require that property owners document the results of an inspection of sumps, pumps, pipes, and slope drains that facilitate drainage away from the crest of the slope at least once every 5 years. If inspections reveal defects, solutions should be implemented before the oncoming rainy season. Maintenance and inspection should also be carried out to ensure that roadside curbs and drains remain free from obstruction and work efficiently. The total annual cost of completing drainage inspections and maintenance along the crest of the escarpment is estimated at approximately $25,000.

The real time rainfall and piezometer monitoring system installed adjacent to the January 2005 landslide should remain active, at least until completion of Stage 2 Remediation. It will provide valuable information regarding groundwater response to antecedent rainfall and periods of intense rainfall. Furthermore, the system will provide a means to monitor against the potential impacts of climate change. At some point in the future, if monitoring data indicate long-term trends in increasing groundwater levels or in the frequency and intensity of rainfall events, adaptation to these changed conditions might be required. The annual operating costs to maintain the monitoring system are estimated at $20,000.

Lastly, DNV should continue to stringently control the cutting of trees on the escarpment. Topping of trees, if done properly, may actually help to improve the stability of the slope by reducing wind loads transferred to the soil. Falling of trees, however, will eventually lead to a loss of root strength and an increase in soil moisture, which will tend to promote instability. In all cases, the trimming and falling of trees should only be carried out with the approval of a professional arborist.

11.0 CLOSURE

This report presents the results of an updated base-case landslide risk assessment for the Berkley Escarpment and an evaluation of options to reduce landslide risk. The results have been calibrated to match the historical record of landslide incidents and provide a defensible framework for the prioritization, design and evaluation of risk control measures, and for ongoing monitoring of risk levels.

A strategy and cost to reduce landslide risks faced by individuals at the top and bottom of the escarpment to less than 10^{-4} per year is provided, as are options to further reduce the risks to 10^{-5} per year. Both targets appear technically feasible, although a period of monitoring to verify the effectiveness of the slope stabilization measures would be required in order to meet the 10^{-5} criteria.

We trust the information provided will allow DNV to proceed with the next steps in the risk management process. Please do not hesitate to contact us if you have any questions or comments, or if we may be of further assistance.

Sincerely,
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Per:

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APPENDIX I

Site Investigation Results

APPENDIX II

Updated Base-Case Risk Estimates

APPENDIX III

Schematic Illustrations and Cost Estimates for Risk Control Options

APPENDIX IV

Risk Estimates Following Completion of Works in Progress

APPENDIX V

Risk Estimates Following Implementation of 10^{-4} Mitigation Strategy

APPENDIX VI

Risk Estimates Following Implementation of 10^{-5} Mitigation Options