QUANTITATIVE BACK-ANALYSIS OF PARTIAL RISK: JAMIESON CREEK DEBRIS FLOW

Jonathan Fannin
Department of Civil Engineering, The University of British Columbia, 6250 Applied Science Lane, Vancouver, B.C., V6T 1Z4, Canada, jonathan.fannin@ubc.ca
Derek Bonin, and David Dunkley
Metro Vancouver, 4330 Kingsway, Burnaby, B.C., V5H 4G8,Canada

RÉSUMÉ
En novembre 1990, des précipitations ont causées un mouvement de débris dans une coupe à blanc dans le réseau de drainage de la rivière Jamieson. Ce mouvement de débris s'est transformé en coulée de débris à mesure qu'il progressait dans ce terrain buché. Par la suite, cette coulée a rejoint le ruisseau Jamieson. Une analyse post-rupture de cet événement, en se basant sur le plan de glissement au point d'origine de l'événement, dans le cutblock, suggère un facteur de sécurité de 0.26. Cette analyse de stabilité se base sur les propriétés du sol mesurées, sur l'interprétation de données piézométriques monitorées ainsi qu'en assumant certains paramètres géotechniques. Les attributs de la pente sous le point d'origine indiquent une probabilité certaine (1) qu'une telle coulée de débris rejoigne le ruisseau Jamieson. L'analyse de la distance de parcours se base sur l'angle de la pente, et un comportement de la coulée qui était non-confinée sur la plus grande partie de son parcours. Par conséquent, l'analyse post-événement montre que le risque pour le ruisseau Jamieson provenant d'une coulée de débris initiée proche du sommet du cutblock, et que cette coulée entre dans le ruisseau, est de 0.26.

ABSTRACT
Storm precipitation during November 1990 caused a debris slide within a forest clearcut in the Jamieson Creek watershed. The debris slide progressed to a debris flow as it moved over the logged terrain, then entered and resulted in sedimentation of Jamieson Creek. Post-event analysis of the factor of safety of a potential failure plane at the point of origin in the cutblock suggests the probability of a specific hazardous landslide occurring, in this case the debris slide, to be 0.26. The slope stability analysis is based on measured soil properties, interpretation of groundwater monitoring data, and some assumed geotechnical parameters. Attributes of the slope below the point of origin indicate the probability of the resulting debris flow entering Jamieson Creek to be certain or 1, given the occurrence of the debris slide. The travel distance analysis is based on a consideration of slope angle, and a flow behaviour that was unconfined for most of the travel path. Accordingly, the post-harvesting back-analysis shows that the partial risk to Jamieson Creek from a debris slide initiating near the top of the cutblock and the resulting debris flow entering the creek to be 0.26.

1. INTRODUCTION AND SITUATION

The Seymour Watershed is one of three watersheds that supply drinking water to 2.1 million people in the Metro Vancouver region. During November 1990, nearly 1500 mm of precipitation fell in the Seymour Watershed, of which 970 mm fell up to November 22nd and 376 mm fell on November 23rd. The antecedent conditions, intense precipitation and melting snow caused many landslides to initiate, both on logged and unlogged terrain during the November 23rd storm.

Jamieson Creek is a tributary to Orchid Creek, which is a tributary to the upper Seymour River. Water quality is the primary objective of management plans for the watershed. Accordingly, the potential for landslide-induced stream sedimentation is a primary concern in land management decisions. The stream reaches downstream of Jamieson Creek in the upper Seymour River contain high quality aquatic habitat and are utilized by salmonids. A combination of landslide-induced stream sedimentation, streambank erosion and shoreline erosion of the reservoir during the storm resulted in unacceptably high turbidity levels in the Seymour Reservoir (Thurber, 1991). The GVRD responded by removing the reservoir, for a period of time, from the water supply system.

One significant landslide that occurred during the November 23rd storm originated in the Jamieson Creek watershed, a sub-drainage of the upper Seymour River. It initiated as a debris slide near the top of a cutblock (Figure 1). The path of the resulting debris flow crossed a logging road approximately 250 m (slope distance) below the headscarp, and continued for approximately 300 m (slope distance) before cutting through an unlogged streamside buffer and entering Jamieson Creek. The ground slope over which it traveled is steep, varying from approximately 31º above the logging road to 22º in the reach preceding entry to the creek. Entrainment of debris was the dominant process along the travel path. Indeed, the logging road presents the only flat ground encountered along the route, and experienced some volume of deposition.

This case study presents a quantitative analysis of partial risk to Jamieson Creek from a debris flow originating within the clearcut and delivering sediment to the creek. The analysis uses data on soil strength and groundwater seepage that were acquired from field studies conducted

In : J. Locat, D. Perret, D. Turmel, D. Demers et S. Leroueil, (2008).
Comptes rendus de la 4e Conférence canadienne sur les géorisques: des causes à la gestion.
Proceedings of the 4th Canadian Conference on Geohazards : From Causes to Management. Presse de l'Université Laval, Québec, 594 p.

after the failure occurred. It makes use of modeling techniques, developed since the failure occurred, to back analyze the debris slide initiation, and the debris flow travel distance.

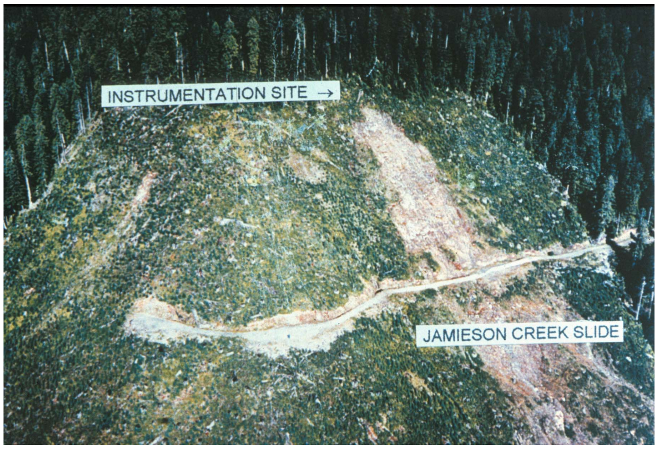

Figure 1. Jamieson Creek landslide - point of origin and initial portion of travel path.

2. GENERAL SITE CHARACTERISTICS

The Seymour Watershed, located north of Vancouver, lies within the Coast Mountain Range and is underlain primarily by quartz diorite (Roddick, 1965). Landform development and geomorphoric processes during and since the end of the Fraser Glaciation, 10,000 to 12,000 years ago, have resulted in the present basin morphology and deposition of surficial sediments. On steep side slopes, the surficial soils overly bedrock and are relatively thin in depth.

The cutblock at Jamieson Creek is located on a south-east to east facing slope. Its upper portion ranges from 740 to 785 m above sea level, in a transient snow zone, and is at the interface between the Coastal Western Hemlock submontane variant (vm1) and montane variant (vm2) boundary (Luttmerding et al., 1990). Prior to logging, the old forest consisted of western hemlock (Tsuga hetrophlla), western red cedar (Thuja plicata), and amabilis fir (Abies amabilis). Data from a hydrometric station situated nearby on the Seymour River, but at a lower elevation, indicate a mean annual precipitation of approximately 3300 mm, with a maximum 24-hour precipitation >300 mm. A ridge in the middle of the cutblock divides the drainage pattern between Orchid Creek and Jamieson Creek. The creeks join 500 meters upstream of the confluence with the Seymour River.

Forest development planning utilized the Aqua Terra Classification System (Briere, 1977) a terrain index system that was a applied at the landscape scale as a slope stability indicator. Indicators of pre-harvest slope instability, including a number of natural occurring landslides adjacent to the proposed cutblock, were noted at the time of layout in 1982. In recognition of these indicators, the boundaries of the cutblock were amended to exclude these areas of erosion from the proposed cutblock. The final layout consisted of a 25 hectare cutblock proposed as a clearcut silviculture system and utilizing a high lead logging method.

Road access was constructed in 1983 with an excavator that was able to sort the organic soil horizons from the glacial till and blasted toe rock, resulting in a stable full bench road grade. The hand-felling of the forest commenced in the fall of 1983 and was completed in 1984. The logging started in the summer of 1984 utilizing a 27 meter highlead tower. The logging continued into the fall of 1984, at which time a small debris flow occurred during a rain-on-snow event that temporarily closed the logging road. The road was subsequently cleared of debris and the logging was completed before the onset of winter. In the fall of 1985 site preparation included burning roadside accumulations of logging slash and a light broadcast burn within the cutblock. In the spring of 1986 hand planting of western red cedar and Douglas-fir (Pseudostuga menziesii var. menziesii) seedlings supplemented the natural regeneration of western hemlock and amabilis fir.

A couple of small landslides that did not reach the road occurred during the post-harvest period from 1986 to 1990. These landslides were initiated above the road where minimal logging deflection occurred to the logs being yarded.

The debris flow that occurred in November 1990, some 6 years after harvesting, initiated as a debris slide on ground having a slope angle (TH) between 28 and 30º (53 to 58%). The steepest section on the locus of slip along the soil-bedrock surface exhibited an angle (α) of 36º (73%) as a result of subtle undulations in the bedrock profile. Subsequent terrain stability mapping delineated the initiation zone as having a high likelihood of landslide initiation after harvesting. In the absence of any slope failures, however, a moderate likelihood of landslide initiation after harvesting would likely have been assigned based on the site attributes.

3. PHOTO-RECORD OF MASS WASTING

Post-landslide rehabilitation was implemented following the 1990 landslide. The residual soil and parent material exposed on the landslide scar provided a challenging growing medium due to raveling soils and a warm summer aspect. Initially, an erosion control grass seed mixture was applied manually and later an aerial hydro-seed mixture was applied. Seedlings were planted only where soil accumulations existed.

Recently, the cutblock experienced mass-wasting during a November 10, 2004 storm. The headscarp of the Jamieson Creek Slide regressed up the slope for approx. 5 meters. Another medium-size landslide was initiated on a steep slope above the road that previously showed some minor erosion. The landslide traveled across the cutblock and was entrained as a debris flow within Orchid Creek to the Seymour River floodplain. An aerial application of hydro – seed mixture was applied during the spring of 2005 to the landslide areas.

Today, tension cracks exist above this new Orchid Creek Slide that suggest more mass wasting will occur in this cutblock in the future.

4. SOIL PROPERTIES

The surficial soils at the point of origin of the debris slide comprise a veneer to blanket of highly weathered colluvium, overlying a discontinuous morainal deposit. The depth (D) of the surficial soils at the headscarp is between 1.0 and 1.5 m, with a mean value of 1.25 m. A dense root mat approximately 0.5 m thick overlies the mineral soils. Exposures along the slide and flow path indicate the bedrock is relatively planar, with small undulations, and slightly weathered. Observations reveal the root mat of the ground surface does not extend significantly into the colluvium, and does not intercept the locus of slip at the soil-bedrock interface. Accordingly, the apparent cohesion attributed to root strength (c_r), and root strength deterioration, are not believed to have been significant influences on stability of the slope (Thurber, 1991). Given initiation within the clearcut, the soils were not subject to any tree surcharge (q_0) loading.

The colluvium comprises many sub-rounded to angular boulders and cobbles in a coarse grained matrix. Visual observations, in test pits and along the headscarp, reveal the cobbles and boulders are lodged individually within this matrix and therefore the matrix of the colluvium is believed to control its mobilized shear strength along the locus of slip. Sieve analyses, on grab samples of the 25 mm minus fraction of the colluvium, indicate the matrix is gravelly sand with some silt and a trace of clay. Grain size curves for three other headscarp locations in coastal British Columbia imply the soil matrix is similar in grain size distribution. Field observations, and experience, were used to assign a range for moisture content (15 to 25%) and dry unit weight (15.7 to 17.3 kN/m^3) believed to be representative of the soil conditions at the point of origin.

In-situ direct shear box tests were performed at the site (Fannin et al., 2005). Results of five in-situ tests on moist undisturbed block samples of colluvium, and two additional laboratory tests on oven-dried reconstituted specimens of the 25 mm minus fraction of the colluvium, are shown in Figure 2. The curves reveal peak strengths at relatively small displacement that diminish to a constant value with further shearing action. The distinct second peak in sample B20712 is attributed to the influence of a root across the plane of shear. A number of other shearbox tests were aborted or discarded because of such influences. The data indicate a mean angle of friction (φ) at large displacement of 46º. The relatively high value is attributed to the influence of a broad gradation of particle size, and low effective stress, on mobilization of shear strength. The soils tested exhibited no cohesion (c_s).

5. GROUNDWATER MONITORING

In 1997, automated piezometers and tensiometers were installed at four instrumentation nests located between 3 and 6 m upslope of the headscarp of the 1990 debris slide, to monitor the post-failure groundwater seepage regime in the soil (Jaakkola, 1998; Fannin and Jaakkola, 1999). The instrumentation recorded positive and negative pore water pressures, respectively, from October 1997 to June 1998. A time series plot of hourly precipitation and groundwater response for the initial two months illustrates well the transition from moist to wet ground conditions with onset of winter storms (see Figure 3). Because the exposed seepage face at the headscarp may have influenced the response of the instrumentation, uncertainty exists as to how well the observed response to storm precipitation describes the site response before the failure.

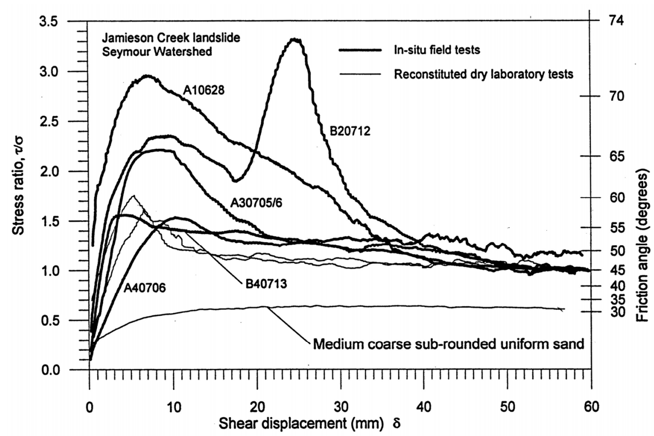

Figure 2. Direct shear box test results on the colluvium (after Fannin et al. 2005).

The resulting data (Figure 3) show that most, but not all, of the responses were closely related to precipitation intensity. The onset of positive porewater pressures, and resulting peak values (of P1, P2 and P3), correlate generally with the onset of precipitation. However, a detailed comparison of maximum porewater pressures during a storm, for example that of October 29th, reveals a very localized response across the short 22 m section of apparently uniform hillslope. The piezometers did not respond in unison to the onset of precipitation. The localized response is attributed to the influence of preferential seepage paths in the surficial soils. The maximum porewater pressure, observed at P1, appears dependent on precipitation intensity and duration. Expressed as a dimensionless groundwater ratio, of pressure head to soil depth (D_w/D), it has a value of 0.7 for the monitoring period. The data confirm the groundwater seepage to be a highly variable parameter, both spatially and temporally. The occurrence of similar peak values of D_w/D in October and November 1997 (Figure 3) suggests this hydrologic trigger to the debris slide has a short return period, and implies the maximum value of D_w/D could be expected to occur annually.

6. PARTIAL RISK ANALYSIS

Partial risk, P(HA), is the product of the probability of occurrence of a specific hazardous landslide <u>and</u> the probability of that landslide reaching or otherwise affecting the site occupied by a specific element. It is defined as:

$$P(HA) = P(H) \times P(S{:}H) \times P(T{:}S) \qquad [1]$$

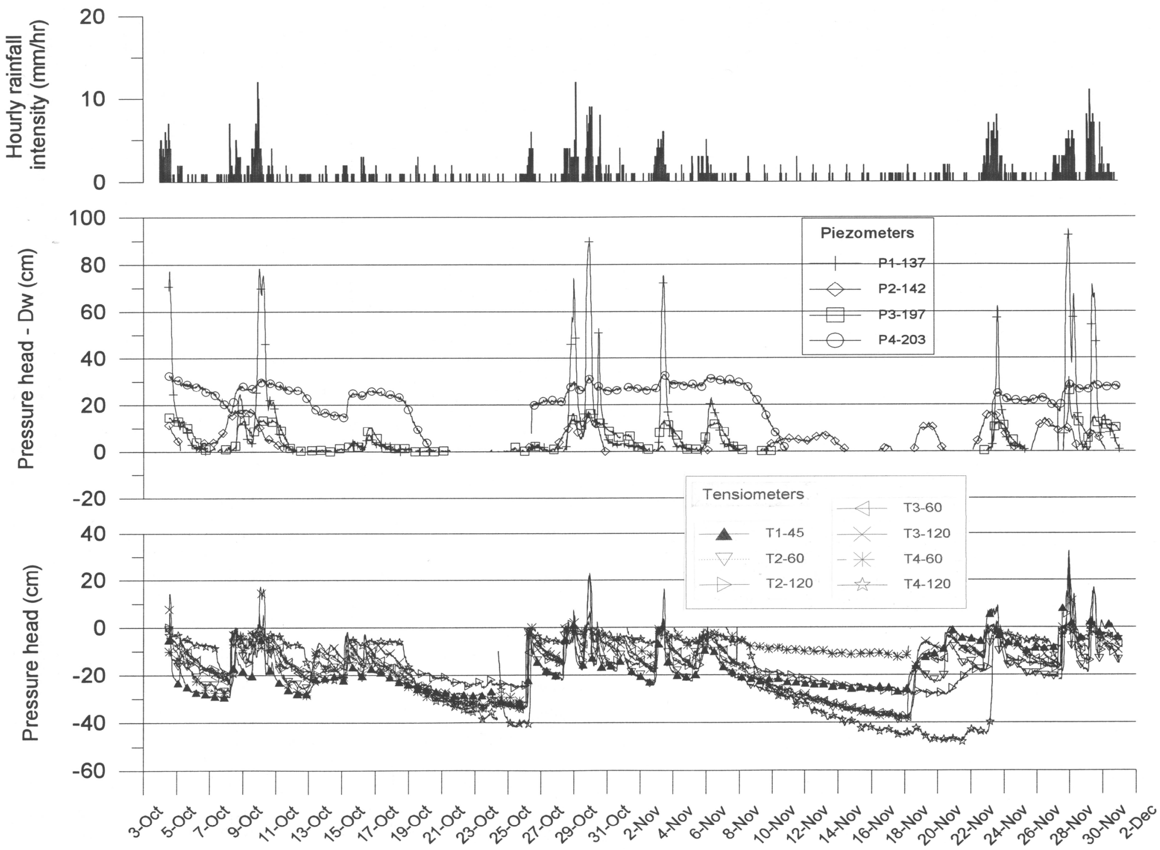

Figure 3. Variation of pore-water pressure and rainfall intensity with time (after Fannin and Jaakkola, 1999).

where,

- P(H) is the probability of occurrence of a specific hazardous landslide;
- P(S:H) is the probability of a spatial effect given that a hazardous landslide occurs; and,
- P(T:S) is the probability of a temporal effect given that a spatial effect occurs.

For this case study, a quantitative partial risk analysis was performed to account for the probability of occurrence of a debris slide at the point of origin, and the probability of the travel distance of the resulting debris flow reaching, or causing an effect at, a point of interest on the slope below. Given the concern for landslide-induced stream sedimentation, the point of interest on the slope below is Jamieson Creek.

6.1 P(H)

At the point of origin, the probability of occurrence, P(H), was estimated as the probability of the factor of safety (FS) being less than unity, P(FS≤1), for an assumed translational slip. The FS was estimated using the infinite slope LISA model, developed by the US Forest Service (Hammond et al., 1992). The LISA model assumes that both the plane of rupture and groundwater surface are parallel to the ground surface, and infinite in extent. LISA is a limit equilibrium analysis that is suitable for sites on planar slopes where the groundwater regime does not result in artesian groundwater pressures. The probability of the FS being less than or equal to one P(FS≤1) was estimated from 1000 calculations of the FS; each calculation was made using random sampling of input parameters, given a user-defined distribution (constant, uniform or triangular) for each parameter and its associated range in magnitude (Table 26).

As noted in the description of general site characteristics, the soil depth, ground slope, tree surcharge, friction angle and soil cohesion values are based on field measurements. The groundwater values are based on limited field observations. The dry unit weight and moisture content are assumed values. A sensitivity analysis was conducted on the contribution of root strength. Three scenarios were examined for the influence of root cohesion: a significant contribution (3.5 to 7 kPa); a moderate contribution (0 to 7 kPa); and, a nominal contribution (0 to 0.5 kPa). As discussed previously, the latter scenario is believed most representative of the site characteristics, given that root strength and root strength deterioration are not believed to have exerted a significant influence on stability of the slope.

The output of the LISA analyses is also summarized in Table 1, with reference to the minimum, mean and maximum FS obtained in the three scenarios for contribution of root cohesion, together with the probability of the FS ≤ 1. The results show P(FS≤1) to increase, from 0.003 to 0.258, with decreasing root cohesion.

Correspondingly, the mean factor of safety diminishes from 1.20 to 1.06. A mean FS = 1.06 implies a significant potential for instability, which is consistent with field observations noted at the time of layout in 1982, and lends further credence to the belief that root strength and root strength deterioration had little significant influence on stability of the slope. Therefore, assuming a nominal contribution of root cohesion at the point of origin, and assuming the groundwater values are representative of the hydrologic conditions in the slope at the time of failure, the P(FS≤1) = 0.258 is considered a reasonable estimate of the probability of occurrence of the specific landslide, P(H).

Table 26. LISA analysis - input variables and probability of failure*.

Parameter	Distribution	Magnitude		
Soil depth, D (m)	Uniform		1.0 – 1.5	
Ground slope, α (º)	Uniform		30 – 36	
Tree surcharge, q_o (kPa)	Constant		0	
Root cohesion, c_r (kPa)	Uniform	3.5 – 7	0 – 7	0 – 0.5
Friction angle, φ´ (º)	Triangular		45/46/47	
Soil cohesion, c_s (kPa)	Constant		0	
Dry unit weight, γ (kN/m^3)	Uniform		15.7 – 17.3	
Moisture content, w (%)	Uniform		15 – 25	
Groundwater (D_w/D)	Triangular		0.6/0.7/0.8	
Factor of safety (FS)	Minimum	0.97	0.88	0.86
	Maximum	1.50	1.50	1.29
	Mean	1.20	1.14	1.06
P(FS ≤ 1)		0.003	0.071	0.258

*Notes: Uniform (min – max); Triangular (min/apex/max), after Hammond et al. (1992).

6.2 P(S:H)

The probability of spatial effect is defined as the probability of the debris flow travel distance exceeding the slope distance from the point of origin to the point of entry at Jamieson Creek, using the UBCDFLOW model (http://www.civil.ubc.ca/ubcdflow). The empirical-statistical model was developed from survey data on forest clearcuts in the Queen Charlotte Islands, British Columbia, using multiple regression analysis (Fannin and Wise, 2001). Recent experience, however, suggests the model may have potential for application to other regions (Eliadorani et al., 2003; Fannin et al., 2006).

To estimate travel distance using this model, it is assumed that, given an initial failure volume, the event magnitude changes as a result of entrainment and deposition of debris along the travel path, and therefore the point of termination can be established as the point at which the cumulative flow volume diminishes to zero. Hillslope morphology is used to assign three types of flow behaviour: unconfined (UF), confined (CF) and transition flow (TF). Flow behaviour and slope angle of the ground surface (TH) determine the occurrence of entrainment or deposition in all reaches of the event path (Table 27).

Application of UBCDFLOW to the Jamieson Creek site implies changes in event magnitude are dominated by one action, since the ground over which the debris flow traveled comprises a series of steep reaches (22º < TH). Accordingly the model assigns entrainment to occur in all but one reach (Figure 4). The exception is the nearly flat, unconfined reach (TH ≈ 2º) of the logging road, where deposition was assigned. The dominant modeled process was one of increasing cumulative flow volume along the travel path, which is consistent with field observations made shortly after the event. Those field observations suggested about 5000 m^3 of debris was entrained above the logging road, of which about 1000 m^3 was deposited on the road, yielding 4000 m^3 that continued downslope to entrain about another 1500 m^3 of debris before entering Jamieson Creek

(Thurber, 1991). The model results (Figure 4) are in remarkably good agreement with the field observations. Since the modeled cumulative flow volume does not diminish to zero along the travel path, a certainty of the debris flow entering Jamieson Creek is implied. Therefore the UBCDFLOW analysis indicates P(S:H) = 1.0.

6.3 P(T:S)

The specific element at risk on the slope, below the point of origin, is Jamieson Creek. Since the creek is a permanent water course, the probability of a temporal effect given a spatial effect, P(T:S), defaults to 1.0.

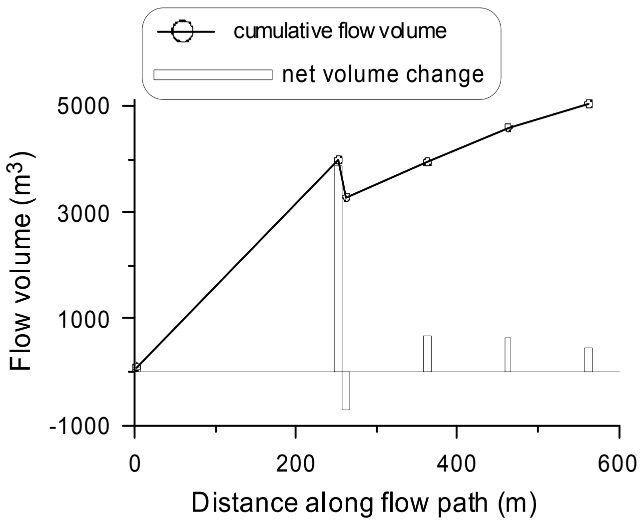

Figure 4. UBCDFLOW - cumulative flow volume along travel path

6.4 P(HA)

The LISA model has been used to quantify the likelihood of debris slide initiation. The UBCDFLOW model has been used to quantify the likely travel distance of the resulting debris flow. Therefore the partial risk of a debris slide initiating near the top of the cutblock, and the resulting debris flow having a travel distance of sufficient length to enter Jamieson Creek, is back-analyzed as the product of P(FS≤1) x P(S:H) = 0.26 x 1.0 = 0.26. Given the nature of spatial and temporal variations in parameters governing both initiation and travel distance, and given assumptions of the models used to quantify the phenomena, P(HA) should be considered only an estimate.

7. RISK EVALUATION AND RISK CONTROL

The LISA model does not explicitly address probability over a specified period of time. Yet some of the input parameters, most notably D_w/D, vary temporally. Accordingly, the output variable of P(FS≤1) reflects the time period over which the user-defined distribution for each input parameter, and its associated range in magnitude (Table 26), are believed to govern stability. Given the occurrence of similar peak values of D_w/D in October and November 1997 (Figure 3), which imply a short return period, and given that groundwater triggered the failure, the value of P(FS≤1) is believed representative of an annual probability of debris slide initiation at this site.

A P(H) = 0.26 for debris slide initiation within the clearcut at Jamieson Creek is calculated with reference to site-specific data on the friction angle of the soil and the groundwater seepage regime. These site data provide for both confidence in the estimated value of P(H) and its interpretation as an annual probability. Field observations correlate a P(H) of this magnitude to indicators of pre-harvest slope instability, including a number of naturally occurring landslides adjacent to the proposed cutblock. In the absence of site-specific data, LISA can be used to determine a P(FS≤1), however the output will be less certain and it should not be considered an annual probability. The spatial variation in the groundwater trigger to failure, D_w/D, observed at Jamieson Creek, confirms preferential seepage in surficial soils to be a critical factor governing the location of failure within terrain polygons.

The UBCDFLOW model was developed from field observations of debris flow travel distance on logged terrain. It is an empirical model, and therefore may be applied with reasonable confidence to logged terrain with attributes similar to those of the Queen Charlotte Islands. If the terrain over which the debris flow travels is unlogged, experience suggests the travel distance is relatively shorter.

Recognizing that root strength, and root strength deterioration are not believed to have exerted a significant influence on stability of the slope, the LISA analysis implies that, in the absence of logging, there was potential for a rainfall-induced failure to occur in the vicinity of the point of origin of the debris slide at Jamieson Creek. However, speculation would suggest that the volume of the failure would likely have been smaller, and the travel distance would likely have been shorter.

8. CONCLUDING REMARKS

The landslide within the cutblock at Jamieson Creek initiated as a debris slide and progressed into a debris flow. Since the event occurred in 1990, the site has been the focus of integrated geotechnical research studies that have yielded detailed information on soil properties, the hydrologic response of the soils to precipitation, the mechanism of failure, and attributes of the downslope travel path. Field monitoring shows groundwater seepage, which triggered the failure, to be a highly variable parameter, both spatially and temporally.

The debris slide initiation occurred as a translational slip, for which the factor of safety was calculated using the infinte slope LISA model, developed by the US Forest Service. A sensitivity analysis confirms root strength and root strength deterioration did not exert a significant influence on stability of the slope. The probability of FS ≤ 1 at the point of origin was estimated to be 0.26. Field observations correlate a

P(H) of this magnitude to field indicators of pre-harvest slope instability, including a number of naturally occurring landslides adjacent to the proposed cutblock.

The travel distance of the resulting debris flow is governed by volumes of entrainment and deposition, and was estimated using the UBCDFLOW model developed at the University of British Columbia. Attributes of the travel path below the point of origin indicate, with complete certainty, that the resulting debris flow would enter Jamieson Creek. The model results are in remarkably good agreement with field observations made shortly after the event.

The quantitative analysis of partial risk is based upon a combination of the probability of FS ≤ 1 at the point origin, and the probability of travel distance exceedance at the point of entry to Jamieson Creek. Accordingly, the partial risk P(HA) to Jamieson Creek from a debris slide initiating near the top of the cutblock, and the resulting debris flow entering the creek, was back-analyzed to be 0.26. Given assumptions of the models used to quantify initiation and travel distance, this partial risk is considered an estimate.

ACKNOWLEDGEMENTS

Fieldwork at the Jamieson Creek cutblock was conducted with funding support from the Natural Sciences and Engineering Research Council of Canada, the Canadian Forest Service, the BC Ministry of Forests and Forest Renewal British Columbia. Additional assistance was provided by the Greater Vancouver Regional District. The authors acknowledge, with thanks, the evaluation of this paper by Dr. Marten Geertsema, Ministry of Forests, British Columbia and Dr. Nicholas Sitar, University of California, Berkeley.

REFERENCES

Eliadorani, A., Fannin, R.J. and Jordan, P., 2003. Debris flows: back analysis of travel distance at Blueberry Creek using UBCDFLOW. *Proc. of the 3rd Canadian Conference on Geotechnique and Natural Hazards*, Edmonton, Alberta, June 8-10, pp.349-356.

Briere, D. 1978. The stratification of forested landscapes for intensive management: development and application. Ph.D. thesis, Faculty of Forestry, University of B.C., Vancouver, B.C.

Fannin, R.J. and Jaakkola, J. 1999. Hydrological response of hillslope soils above a debris-slide headscarp. *Canadian Geotechnical Journal*, Vol. 36, No.6, pp.1481-1494.

Fannin, R.J. and Wise, M.P. 2001. An empirical-statistical model for debris flow travel distance. *Canadian Geotechnical Journal*, Vol. 38, No. 5, pp.982-994.

Fannin, R.J., Eliadorani, A. and Wilkinson, J.M.T. (2005). Shear strength of cohesionless soils at low effective stress. *Geotechnique*, Vol. 55, No.6, 467-478.

Hammond, C., Hall, D., Miller, S. and Swetik, P. 1992. Level 1 Stability Analysis (LISA) documentation for Version 2.0. United States Department of Agriculture, Forest Service, Intermountain Research Station, General Technical Report INT-285, 190p.

Jaakkola, J., 1998. Forest groundwater hydrology: implications for terrain stability in coastal British Columbia. M.A.Sc. thesis, Department of Civil Engineering, University of British Columbia, Vancouver, B.C.

Luttmerding, H.A., D.A. Demarchi, E.C. Lea, D.V. Meidinger, and T. Vold (Eds.) 1990. Describing Ecosystems in the Field. Second Edition, B.C. Ministry of Environment Manual 11, B.C. Ministry of Environment, Victoria, B.C.

Roddick, J.A., 1965. Vancouver North, Coquitlam, and Pitt Lake Map-Areas, British Columbia. Memoir 335, Geological Survey of Canada, 276p.

Thurber Engineering, 1991. Geotechnical Assessment of 1990 – 1991 Landslides Events in Greater Vancouver Water District Watersheds, Report to GVWD.

UBCDFLOW – http://www.civil.ubc.ca/ubcdflow