Characterization of debris slope failures: An integrated field based numerical modelling study

Caractérisation des ruptures de pente en débris: Une étude intégrée de travaux de terrain et de modélisation numérique

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ABSTRACT
In the Interior of British Columbia debris slope failures have been frequently noted to occur at marked transitions in slope gradient, often termed « gentle over steep slopes ». Steady state and transient groundwater modelling analyses were conducted using SEEP/W. The result from the groundwater modelling was coupled with both limit equilibrium analysis and finite element slope deformation models. A second component of the current research program is the field characterization and the rheological modelling of runout associated with open slope debris flows. Field data from Vancouver Island was used to conduct a back-analysis with the code DANW of specific failure to determine their rheological input. The results of these analyses are compared against published debris flow analyses data.

RÉSUMÉ
Dans l'intérieur de la Colombie Britannique les ruptures de pentes en débris sont fréquemment observées à une transition marquée du gradient de la pente, souvent nommé « pente douce sur raide ». Des modélisations de condition d'écoulements permanentes et transitoire de des eaux souterraines furent conduites utilisant SEEP/W. Les résultats de la modélisation des eaux souterraines furent intégrés aux méthodes d'équilibre limité et d'élément finis de déformation des pentes. Un deuxième volet du programme de recherche courant est la caractérisation sur le terrain des longueurs de déposition des pentes et leur modélisation rhéologique. Les données de terrain de l'Ile de Vancouver furent utilisées pour un rétroanalyse de ruptures spécifiques utilisant le code DANW pour déterminer leurs intrants rhéologiques. Les résultats de ces analyses furent comparés avec les données publiées sur les coulées de débris.

Keywords : numerical modelling, runout, groundwater conditions, landslide

1 INTRODUCTION

Debris slope failure (debris flows, debris avalanches and debris slides) form significant hazards in the mountainous areas of British Columbia and may have an important impact on the harvesting of forested slopes. The analysis of debris slope failures is usually undertaken from either the perspective of the factors triggering failure or the extent of the resulting runout. During the last 6 years a research program at Simon Fraser University has involved field investigation of debris slope failures in both in the Interior (Site 1 in Figure 1) and the coastal areas of Vancouver Island of B.C. (Site 2 in Figure 1).

2 METHODOLOGY

2.1 *Fieldwork based groundwater-slope stability modelling*

Gentle-over-steep, G-o-S, topography, Figure 2, has been recognized as an important factor in the stability of harvested slopes. As part of a study on the factors influencing gentle-over-steep slope failures 25 G-o-S failures within the B.C. Interior region were studied in detail. Data was collected under the following headings:

1. General Landslide Information
2. Terrain Mapping Information
3. Air Photo Information
4. Downslope Consequences
5. Landslide Characteristics
6. Logging Road Information
7. Slope Angle and Slope Distance
8. Landslide Dimensions
9. Slope Shape and Form
10. Evidence of Water on Slope
11. Bedrock Types and Soil Classification
12. Landslide Photos and Sketches

Particular emphasis during field work was placed on investigating relationships between topography, soil stratigraphy/characteristics (particle size distribution and Atterberg limits), road location with respect to slope failures, road drainage and groundwater. These observations were then used as basis for a conceptual modelling study to explore the influence of groundwater flow on slope failure in G-o-S slopes. The methodology adopted is illustrated in Figure 2 and progressed from transient groundwater models using SeepW to slope stability analysis. Input for groundwater flow models was based on combined field and laboratory data and the use of the available hydraulic properties from soil grain size library within SeepW. Groundwater models allowed the assumption of both groundwater table/seepage face locations and pore water pressures into both limit equilibrium and finite element codes. The former provided information on the role of groundwater seepage on slope failure below the G-o-S slope break and the sensitivity analyses on the resulting factor of safety with respect to assumed and modeled groundwater conditions.

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The landslide runout path was divided in reaches of similar characteristics in a manner similar to the one used by Fannin and Wise (2001). The landslide data cards developed by the BC Ministry of Forests were used to collect and compile the field data. A photographic record of each landslide was acquired and soil samples were collected from the headscarp and deposit

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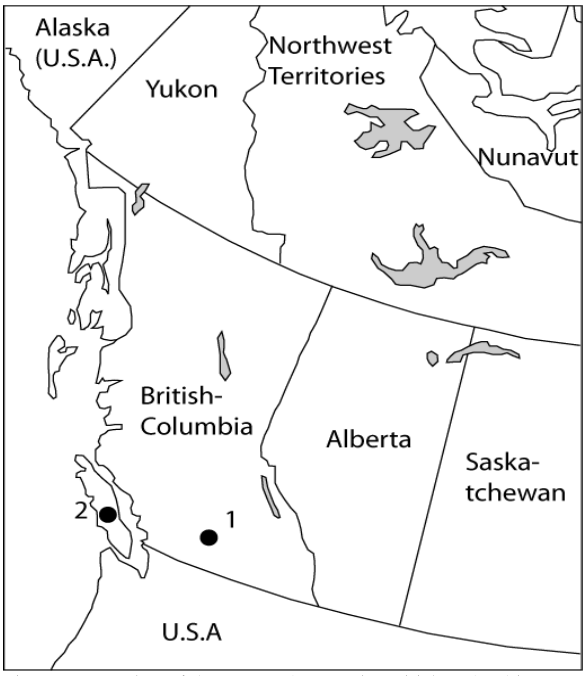

Figure 1. Location of the two study areas in British Columbia, Canada.

3 RESULTS

3.1 *B.C. Interior Project*

Table 1 shows the observations summarized from a detailed analysis of the field data, Paddington (2003). Limit equilibrium analyses conducted using static water tables in both infinite slope and circular limit equilibrium codes showed that in the 1 to 2 m thick soil profiles the elevation of the water table was far less critical than the seepage gradient and result seepage pressures associated with downslope groundwater flow. The use of the finite element code Phase2 allowed a conceptual study of the role of groundwater pressures on predicted deformation below G-o S slope breaks. Results of these simulations show not only the location of potential debris flows but an indication of the extent of failures. The next ongoing stage was to assess the influence of groundwater seepage on the shear strength reduction factor of safety and to provide initiation volume estimates as input for subsequent runout modelling using DANW. Initial analyses had imported groundwater pressures undertaken using Seep3D into SLIDE and PHASE2 (Scibek, 2004). Sections through the Seep3D models confirmed the important role played by slope hollows behind G-o-S slopes in channeling seepage and the resulting higher groundwater pressures below G-o-S slope breaks with a concomitant reduction in slope stability. Figure 3 shows conceptually the simulated role of groundwater seepage on the initiation of slope failure below G-o-S slope breaks and slope hollows. The results of the groundwater-mechanical simulation are in agreement with the physical principles discussed by Iverson and Major (1986).

3.2 *Vancouver Island Project*

The volume distribution for the 35 landslides investigated displayed a weak log-normal distribution with a peak for events between 250-500m^3. This was attributed to the higher frequency of smaller events. The lower number of events below 250-m^3 was attributed to a censoring of the size of event that was recorded in the field. The elevation difference (ΔH) divided by the travel distance (L) is a commonly quoted number for large landslides (Scheidegger, 1973). It is generally accepted that the larger the volume of the landslide the smaller

Table 1. Common characteristics of landslides on Gentle-Over-Steep terrain.

Characteristic	Description
Precipitation and Antecedent Conditions	Landslide initiation occurred in the spring and early summer months, during periods of short-term precipitation, rain-on-snow events, and during uncharacteristically wet years. The majority of the landslides occurred in 1990, 1997, and 2002
Logging road	The cutslope was most commonly excavated into bedrock or lodgement till. All runoff and near surface groundwater were intercepted by the logging road. Culvert spacing should ensure adequate drainage of the intercepted water.
Trigger	Collected and redirected natural surface and groundwater by forest development operations were identified as the most common landslide trigger.
Forest Cover	Forest cover above the logging road at most sites had been clearcut, while below the road and at the initiation zone the slopes were forested.
Landslide Type	Landslide type distribution consisted of 19 debris avalanches and 6 debris flows.
Surficial Material Thickness	Surficial material consisted of a thin veneer to blanket of unconsolidated morainal material (primarily unweathered till) rich in sand and gravel overlying a blanket of consolidated morainal material (primarily lodgement till) rich in sand and gravel or bedrock.
Slope Form	The shape of the slope down from the logging road was most commonly planar or convex. Across the slope was most commonly gullied, indicating the potential for water to concentrate in topographic lows.
Slope Distance	The distance between the logging road and initiation zone was generally less than 200m. The break-in-slope was generally less than 115m from the logging road and the initiation zone was less than 62m below the break-in-slope.
Slope Angles	The gentle slope was variable and within the gentle to moderate (4º to 27º) slope range. The steep slope was between 23º and 50º when failure was within 60m of the break-in-slope and less than 35º when the failure was greater than 60m from the break-in-slope.
Volume and Landslide Length	Volumes of debris removed from the initiation zone were less than 200 m^3. The length of the initiation zone was less than 50m while runout could be up to 800m for debris avalanches and 4000m for debris flows.
Terrain Classes	The gentle slope and location of the logging road was most commonly classified as Terrain Stability Class II and III, while the steeper slopes below the break-in-slope were classified as Terrain Stability Class IV and V.
Consequences	Most commonly impacted were harvestable timber and fisheries. Also note the significance of human life and property.

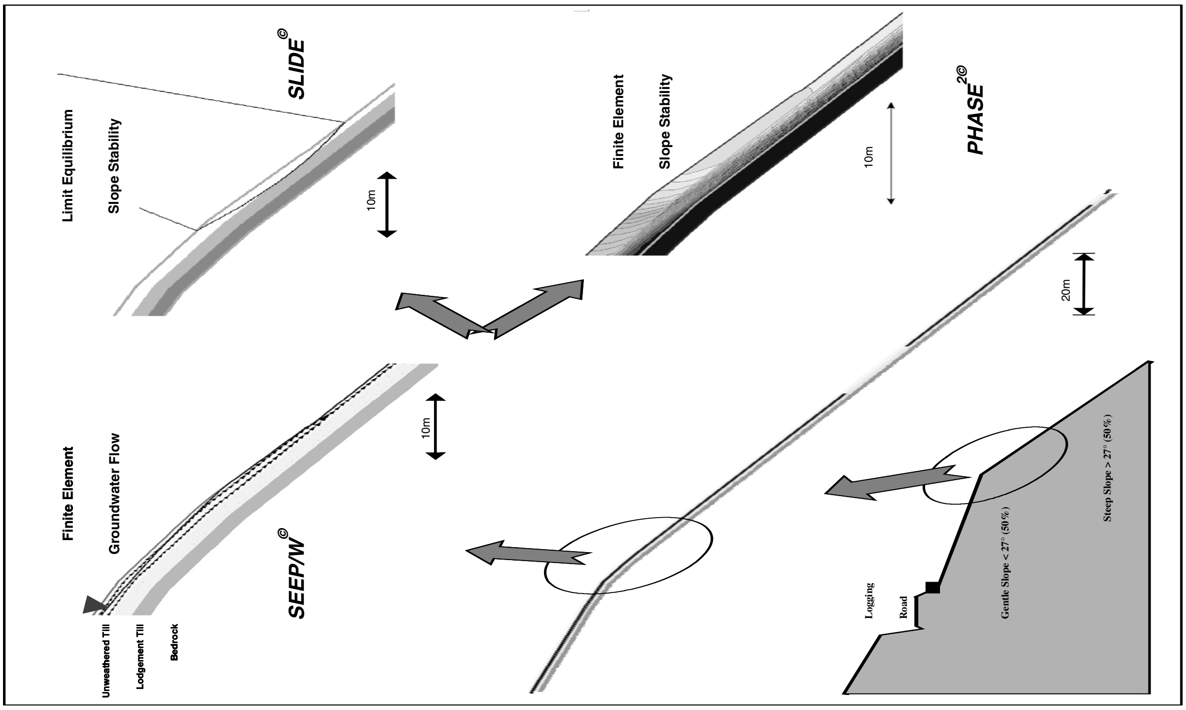

Figure 2. Typical simulation data from integrated groundwater models with limit equilibrium and finite element models.

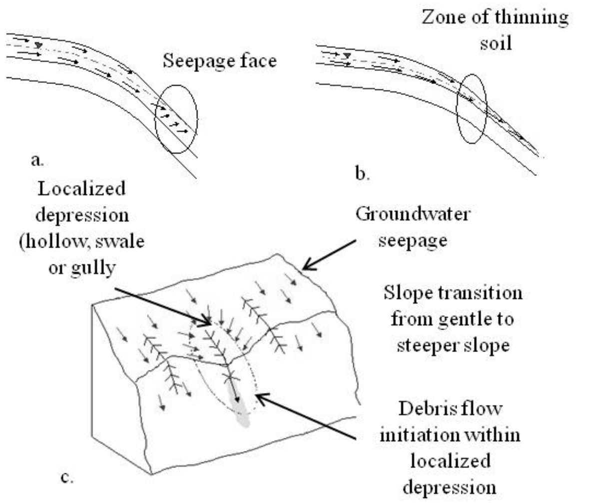

Figure 3. Critical modeled groundwater seepage G-o-S conditions leading to debris flows/avalanches a. seepage below slope break, b. thinning soil layer causing seepage face c. topographic hollow above slope break.

the ΔH/L ratio (Scheidegger, 1973; Corominas, 1996). In Vancouver Island, a similar relationship was observed for landslides with a deposited volume greater than 500 m^3 while no relationship was observed for smaller landslides (Figure 4). A similar dependence on volume was noted by Finlay et al., (1999) for small landslides in Hong Kong.

The headscarp stratigraphy of the 35 landslides visited consisted of weathered till or colluvium (60-70cm) underlain by unweathered till (0-100cm) and bedrock. Samples of weathered and unweathered surficial material along with the deposits (where no significant re-working had occurred) were collected from the Vancouver Island field area. The results of the particle size distribution analysis are summarized in Figure 5. The soil material was dominantly composed of gravel and sand with all collected sample have less then 10% of silt and clay. The soil samples were well graded. No significant control by weathering on soil composition was observed.

3.2.1 *Dynamic modelling*

DANW is a one-dimensional dynamic analysis numerical modelling software developed by Hungr (1995) to estimate the runout of rapid flow slides, debris flows and avalanches. DANW represents rapid landslide movement as a continuum equivalent fluid and uses the Lagrangian solution to the St-Venant equations of motion. The heterogeneity in the landslide is represented by an equivalent material which yields the same dynamic component (velocity) and deposit geometry (runout distance, thickness of the deposit) as observed in the field (Hungr, 1995).

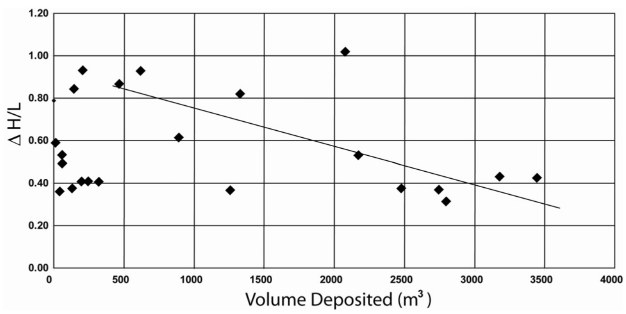

Figure 4. ΔH/L plot for the landslides visited on Vancouver Island.

A series of back-analysis were performed on 23 of the 35 landslides visited. The landslide geometry measured in the field was used as input in the DANW models. Runout distance and velocity estimates were the two field parameters used to constrain the models. In this project only runout distances were measured directly, so an arbitrarily value of 10 m/s was chosen for the maximum velocity. Figure 6 compares the back-calculated angles of friction from frictional models of some of the landslides visited on Vancouver Island with results from Ayotte et al. (1999) for small landslides in Hong Kong and large rock avalanches (Hungr and Evans, 1996). Both set of values for small debris avalanches have similar ranges.

The effective friction angles of large rock avalanches were larger. While a good fit between the observed and modeled runouts was achieved the velocities in the models were consistently in the order of 20 to 30 m/s. Velocity overestimation was also encountered by Bertolo and Wieczorek (2005) in preliminary runs of models of debris flows using only a frictional rheology.

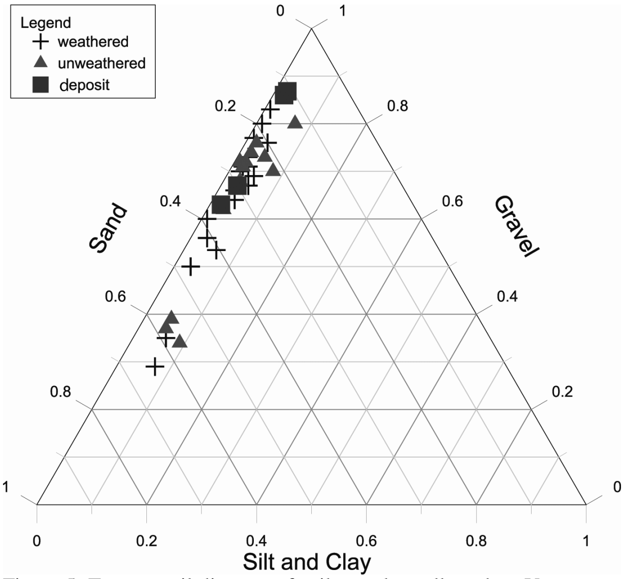

Figure 5. Ternary soil diagram of soil samples collected on Vancouver Island.

A graph of the input values used in the runout modelling of the Vancouver Island landslides using the Voellmy rheology is presented in Figure 7. Input values used by Ayotte et al., (1999), Revellino et al. (2004) and Bertolo and Wieczorek (2005) for small landslides and by Hungr and Evans (1996) for large rock avalanches are also plotted for comparison. The previously published values do not correspond well with the back-analysis performed on the Vancouver Island landslides. There are three possible explanations for this discrepancy. i) the data from Ayotte et al. (1999) and from Bertolo and Wieczorek (2005) are for confined debris flows. ii) the data from Revellino et al., (2004) models debris flow and debris avalanches in pyroclastic material with a larger volume than the Vancouver Island ones. iii) no velocity values were available to constrain the models of the Vancouver Island landslides, an arbitrary value of 10m/s was used.

4 CONCLUSIONS

The results of the field studies on both debris flow initiation and runout have provided important practical data on the factors influencing debris failures in slopes. The importance of surface and subsurface drainage in forest slope environments, particularly at marked transitions in slope gradients has important implications for forest road drainage practices. The use of a coupled transient groundwater-limit equilibrium – finite element approach has enable the influence of varying gentle over steep geometries to be investigated and to further our understanding of groundwater-induced debris slope failures. A detailed field numerical study of debris slope failure debris runout has similarly provided extremely useful data for estimating potential runout extents from forest slope failures. The proposed total slope analysis approach, linking predicted initiation volumes with rheologic runout models, is believed to offer significant advances in the analysis of forest slopes and successful resource and infrastructure development.

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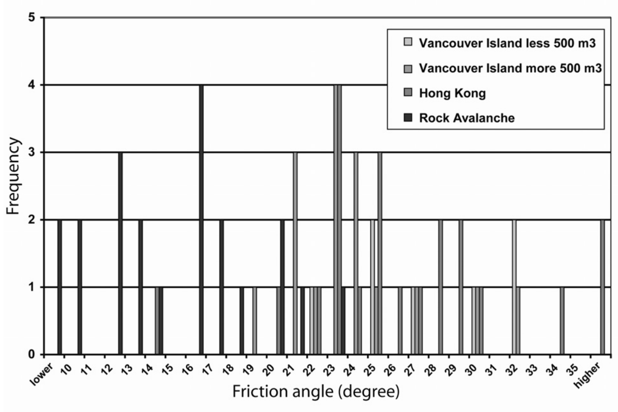

Figure 6. Friction angle values that correspond most closely to runout distance using frictional material rheology.

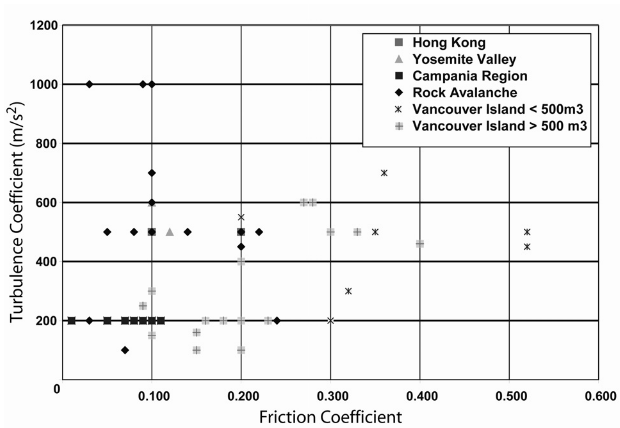

Figure 7. Plot of input values used for modelling using Voellmy rheology.

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