PRELIMINARY CALIBRATION FOR FINITE DIFFERENCE MODELLING OF DOWNIE SLIDE

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ABSTRACT
A GIS platform is currently being developed for compiling, monitoring and interpreting data trends collected from instrumentation on large landslides. Downie Slide, near Revelstoke, British Columbia, provides an excellent pilot case for testing these approaches due to its extensive array of instruments, 25 years of monitoring data, good geological control, and a well understood geometry and sliding mechanism.

A finite difference analysis is being used to establish the potential impacts of changing conditions on the slide mass movement, and therefore determining 'normal' data trends and limits for use in the GIS. Historically, the stability of Downie Slide has been monitored using instrumentation data and site reconnaissance, and assessed using limit equilibrium analyses. As a result, important input parameters and functions for a finite difference model have not been previously defined. Work to date has included preliminary parameter investigation and model calibration to define appropriate constitutive models.

RÉSUMÉ
Une plateforme SIG est actuellement en développement pour receuillir, controler et interpreter les tendances dans les données collectées par des capteurs sur de larges glissements de terrain. Le site de Downie Slide, près de Revelstoke en Colombie Britannique, fournit une excellente étude pilote pour tester cette approche, ceci grâce à son large maillage de capteurs, 25 ans de contrôle de données, et une bonne connaissance de la structure géologique et du mécanisme de glissement de terrain.

Une analyse par différences finies est actuellement utilisée pour établir les impacts potentiels de changements de conditions sur le mouvement de la masse en glissement, et ainsi déterminer les tendances "normales" dans les données, ainsi que les limites d'utilisation du SIG. Par le passé, la stabilité de Downie Slide a été contrôlée en utilisant des données issues de capteurs et des observations sur le terrain, et évaluée par des analyses d'équilibre aux limites. Néanmoins, des fonctions et des paramètres d'entrée importants pour des modèles par différences finies n'ont pas été définis jusqu'à présent. Les travaux menés à ce jour comprennent l'étude préliminaire des paramètres et la calibration du modèle, afin de définir les modèles constitutifs appropriés.

1. INTRODUCTION

Sensor networks and Geographic Information Systems (GIS) technology are increasingly being applied to problems of slope stability. In cases of complex slopes and real-time data acquisition from numerous sensors and sensor types, a rule-based decision support system (DSS) can aid an expert in ongoing monitoring of potential instabilities, and in back analysis of historically recorded data. This project, part of a research initiative into sensor data fusion and decision support, focuses on using case studies to determine reasonable geotechnical rules for use in the GIS-DSS tools. In particular, the slow moving rock slope known as Downie Slide, near Revelstoke, BC, provides a site with abundant historical sensor data and good engineering control.

Finite difference modelling was used to assess the potential impact of changing conditions on the slope stability. This model type is expected to simulate the cumulative effects of the geologic history of the area and to support kinematic interpretations of the landslide movement. Development of this model has been challenging, mostly due to limited knowledge of appropriate material properties. As a result, an extensive review of previous geologic studies of the area has been conducted, and the information found has been incorporated into the methodology described here for modelling this large rockslide.

2. SLIDE HISTORY AND GEOLOGY

The Columbia River drainage basin between Revelstoke and Mica Creek was explored in the 1960s by BC Hydro to determine the effects that a downstream blockage created by a landslide might have on the Mica Dam. Downie Slide, amongst other potentially unstable slopes, was discovered approximately 60 km downstream during this time. In 1973, as the reservoir behind Mica Dam began filling, BC Hydro's focus shifted downstream to the newly proposed Revelstoke Dam. Mapping, investigative drilling, slope movement indicator measurements, groundwater measurements, and mechanical testing of

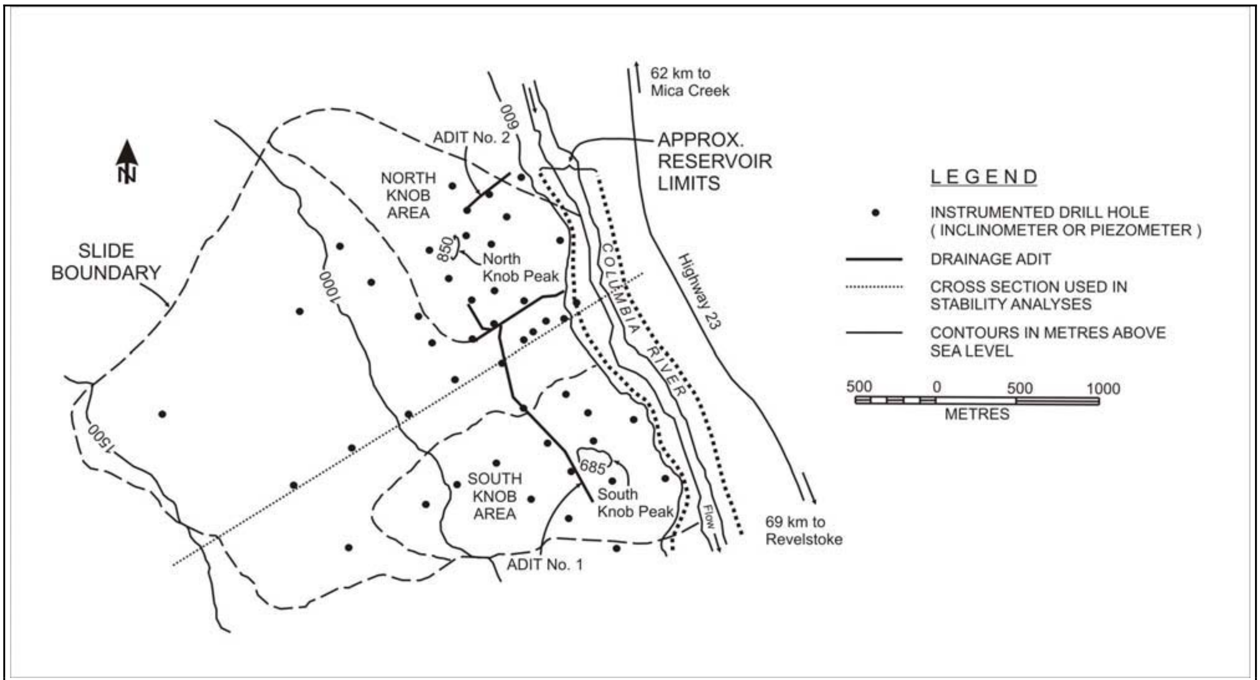

Figure 1. Plan of Downie Slide, showing the location of instrumented drill holes, drainage adits, north and south knobs, and the alignment of the cross section used in the numerical analysis (after Imrie et al, 1991).

rock samples were undertaken to determine the possible effects of a slope failure as a result of impoundment of the new reservoir (Imrie, 1983). The principal concern was related to the potential for a rapid slide failure to generate a wave that could overtop the dam.

Downie Slide (Figure 1) measures 2.4 km along the Columbia River and 3.2 km from toe to headscarp (Moore, 1989). The headscarp, along the west edge, measures up to 160 m in height, and is indicative of substantial historical movement. Estimates of the total area of the slide mass range from 7.5 to 9 km^2, and borehole

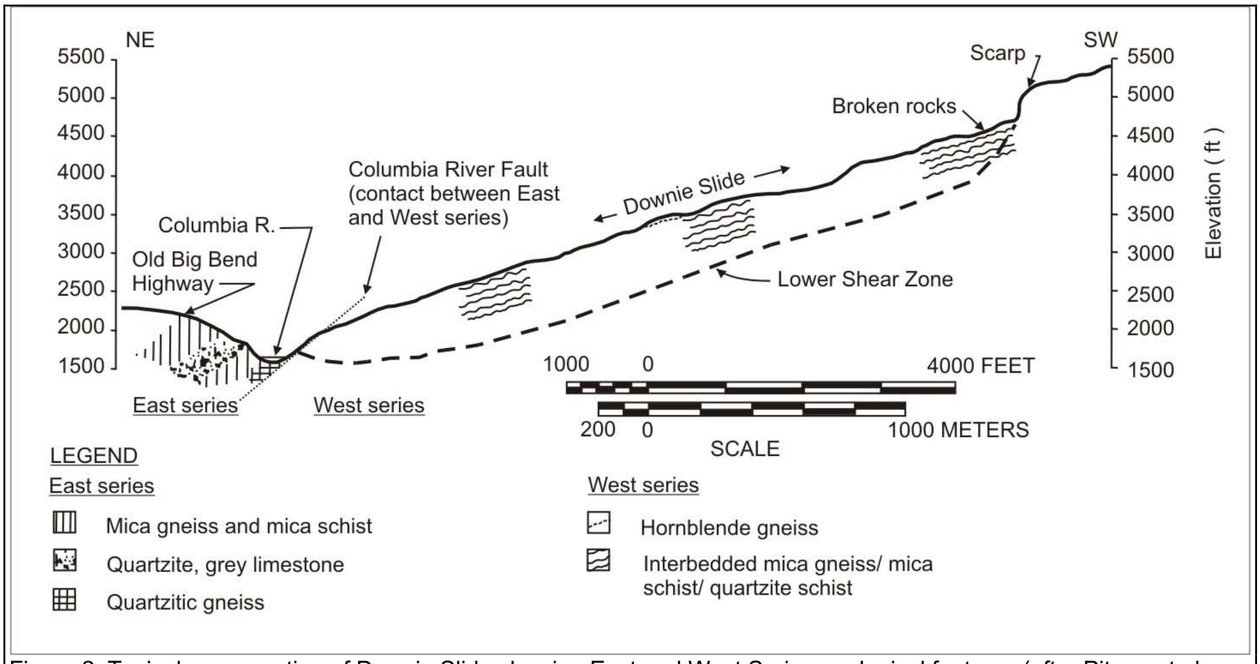

Figure 2. Typical cross section of Downie Slide showing East and West Series geological features (after Piteau et al., 1978).

inclinometer measurements indicate that the mass is up to 245 m thick, leading to an estimated volume of 1.5 x 10^9 m^3 (Imrie, 1983; Piteau et al, 1978). The slide is characterized by an irregular head scarp that decreases in height towards the north, and curves east to form the north scarp. The south flank is defined by a westerly trending scarp face that increases to a height of about 150 metres as it goes west. The north and south knobs comprise two distinctive areas within the sliding mass. The north knob, located at the upstream toe, rises to a distinct peak, and is composed of relatively strong rock, whereas the south knob, located at the downstream toe, is a rounded ridge covered with disturbed slabs of rock.

The bedrock stratigraphy (Figure 2) consists of high-grade metamorphic interlayered, well-foliated mica gneisses, mica schists and quartzites belonging to the Shuswap Metamorphic Complex. The Columbia River Fault, in the region of Downie Slide, dips 20 to 30° to the northeast and contains zones of weak, sheared and brecciated rock (Moore, 1997). This fault serves as the contact between the Monashee complex (West Series) and the Selkirk allochthon (East Series). The rock is moderately blocky and seamy, with alternating bands ranging from 0.1 m to over 10 m thick. The foliation generally dips easterly towards the river at an angle of 18°, but is locally disrupted by intricate complex folds and small-scale faults (Imrie et al., 1991; Lewis and Moore, 1988; Imrie, 1983; Moore, 1989; Piteau et al., 1978). The gneisses and quartzites are hard and brittle, whereas the mica schist is soft and yielding. Sheared seams containing gouge (1 mm to 150 mm thick) are common, joints that cross cut the foliation are widely spaced, and the schist is highly erodible when sheared or when exposed to flowing water (Lewis and Moore, 1988). The base of the slide is defined by a large continuous sheared and brecciated 'Lower Shear Zone' some 15 m to 20 m thick. The shear zone is subparallel to both the foliation and ground surface and contains seams of plastic silty clay gouge.

The Columbia River Valley has been exposed to several episodes of glaciation, the last of which was the Wisconsin glaciation era. During the maximum extent of this era, about 10 000 years ago, the region was covered by the Cordilleran ice sheet to an elevation of about 2600 m, and the bedrock surface was eroded as much as 60 m below the present channel (Moore et al., 1997; Lewis and Moore, 1988; Piteau et al., 1978; Fulton, 1968). The glacial activity scoured a U-shaped valley along the Columbia River Fault, and filled it with terraces of glacio-fluvial and glacio-lacustrine deposits.

It is believed that movement was initially triggered at Downie Slide during glacial recession and not post-glacial origin. A popular hypothesis is that the upper two thirds of the slide could have started moving when the valley was still filled with ice up to an elevation of between 625 and 940 m. Some evidence supporting this theory is outlined by Piteau et al. (1978) as follows:

- The presence of the south and north knobs (Figure 1): without the restraint of movement created by glacial ice the rock in these regions would translate with the rest of the slide mass, rather than bulge.

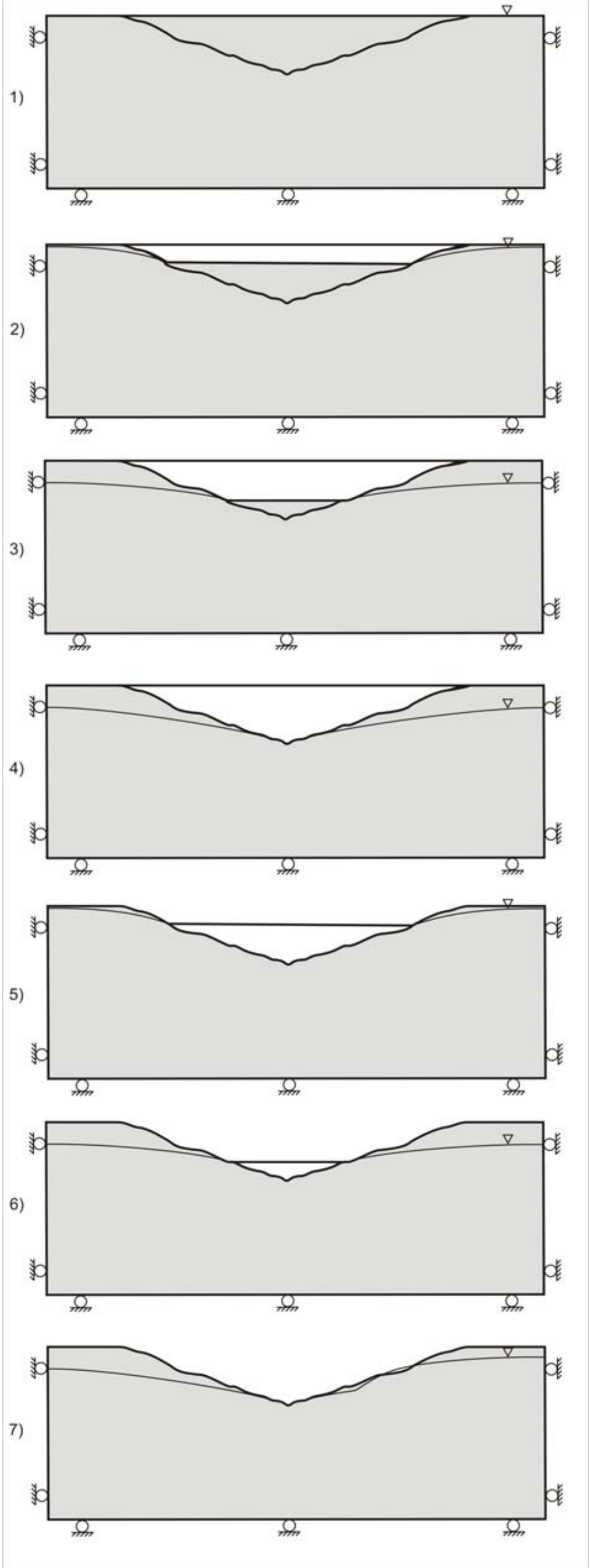

Figure 3. Process of simulating glaciation and glacial retreat in FLAC. Grey regions represent the rock mass, whereas enclosed white regions represent glacial ice.

- The absence of slide material on the east bank of the river, opposite the slide: an unrestrained movement would likely result in debris traveling to the other side of the valley, whereas in the case of Downie Slide, there is none.
- The absence of geological evidence for a slide dammed lake in the valley: indicates that large scale blockage of the river has not occurred.

It is therefore believed that movement began at the onset of glacial recession, and has continued since. It is not clear whether this continued movement has been constant or episodic.

3. MODELLING METHODOLOGY

To replicate the complex geological history of the site, and to project future movements, modelling was carried out using FLAC (Itasca, 2001) based on the explicit finite difference method. The models were designed to examine the influence of glacial ice movement on the stability of the slide mass. The recent movement history of Downie Slide has been examined using groundwater monitoring, movement monitoring, and site reconnaissance; and the stability modelling to date has been based on limit equilibrium approaches. As a result, many of the input parameters required in the finite difference method for various constitutive relationships have not been previously defined, such as bulk and shear moduli, dilation angle, and tensile strength. A modified methodology, similar to analyses by Agliardi et al. (2001) and Eberhardt et al. (2004), was therefore implemented for the input of numerous material parameters and assumptions regarding the geological history of the region, in order to develop a model calibrated to mechanisms observed in borehole investigations as well as from instrument data.

A representation of the rock mass, represented by material properties typical of lowest strength material within the slope, was first developed and the computer program was run to equilibrium in order to minimize inertial effects. Glacial histories (Figure 3) were then simulated by the advance of an ice sheet represented by sequentially changing the material parameters for the upper portions of the valley to represent ice instead of rock. The resulting slope profile was one that was restored to a reasonable ‘glacial age’ condition (Piteau et al., 1978), taken as an initial geometry for the simulation. Glacial retreat was simulated by sequentially deleting the upper layers of the ice. During recession, a parabolic groundwater table that intersected the slope profile at the elevation reached by the glacier surface was assumed. Each stage was given enough time-steps to allow for unbalanced forces within the model to dissipate.

Once the entire valley was formed to the surface of the postulated glacial deposits (i.e. immediate post glacier conditions), a water table representative of that measured at the Downie Slide site was implemented upon completion of the deglaciation stage. The model of the site, with an unobstructed valley, was then allowed to cycle to explore subsequent movements, stress concentrations, and material failure.

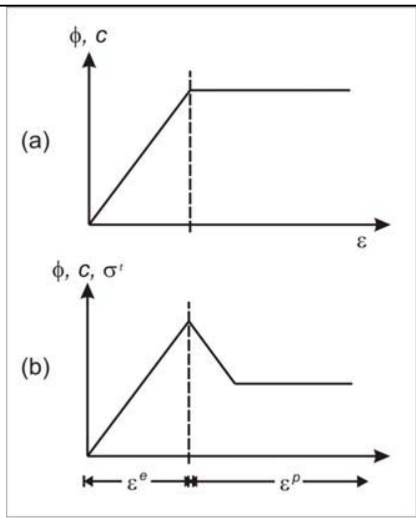

Figure 4. Schematics showing relationship between strain and material properties for (a) elasto-plastic M-C and (b) elastic, strain softening M-C constitutive laws.

Within this model framework, parameter inputs obtained from laboratory tests (Enegren and Imrie, 1995), from a review of the literature, and based on empirical methods such as the Geological Strength Index (GSI) were imposed. These values were input into the model with various constitutive relations to examine the effects of rockmass strengths and behaviours on the rate and degree of movement within the slide. The results of each parametric analysis were visually calibrated against a cross section of the slide interpreted from ground surveys, borehole investigations and the results of insitu monitoring. Through this visual calibration, the suitability of each constitutive model was determined. Information obtained from each analysis was considered before subsequent runs for other models were designed and implemented.

4. ELASTIC, PERFECTLY PLASTIC MOHR-COULOMB MODEL

The elastic, perfectly plastic (elasto-plastic) Mohr-Coulomb (M-C) relation (Figure 4a) was implemented in the model first, as it was used for the previous limit equilibrium studies, and because only a limited number of material parameters are required. This results in a relatively simple parametric analysis, as there are fewer parameters to vary, and the limits of the parameters are relatively well constrained. This constitutive relationship requires definitions of the elastic bulk modulus (*K*), elastic shear modulus (*G*), rock mass cohesion (*c*), internal angle of friction (ϕ), tensile strength (σ^t), density (ρ), and dilation angle (ψ). Friction, cohesion, and tensile strength values were the inputs varied in a parametric analysis. The parameters used in the modelling are presented in Table 1.

Table 1. Rock mass values employed in elasto-plastic Mohr-Coulomb analyses.

Property	Lower Limit	Upper Limit	Interval Size
Bulk Modulus, K (GPa)[1]	1.852	-	-
Shear Modulus, G (GPa)[1]	1.754	-	-
Density, ρ (kg/m^3)	2700	-	-
Dilation Angle, ψ[1]	0°	-	-
Friction Angle, ϕ:	15°	45°	7.5°
Cohesion (kPa):	0	500	100
Tensile Strength, σ^t (kPa):	0	400	200

[1]represents values that were not varied parametrically

The large ranges of values were chosen to explore the applicability of values reported in the literature from different sites with similar rock types, to assess the viability of using values from previous limit equilibrium methods, and to explore the effects of uncertainty and variability in the geology on a single cross section. Conducting a large amount of runs for a considerable range of values was most easily done using the elasto-plastic M-C constitutive relation due to the limited number of parameters required, as well as the rapid run times.

The results show that, in tensionless materials, unrealistic grid distortion causes the program to terminate, thus restricting the model's ability to converge. This is likely

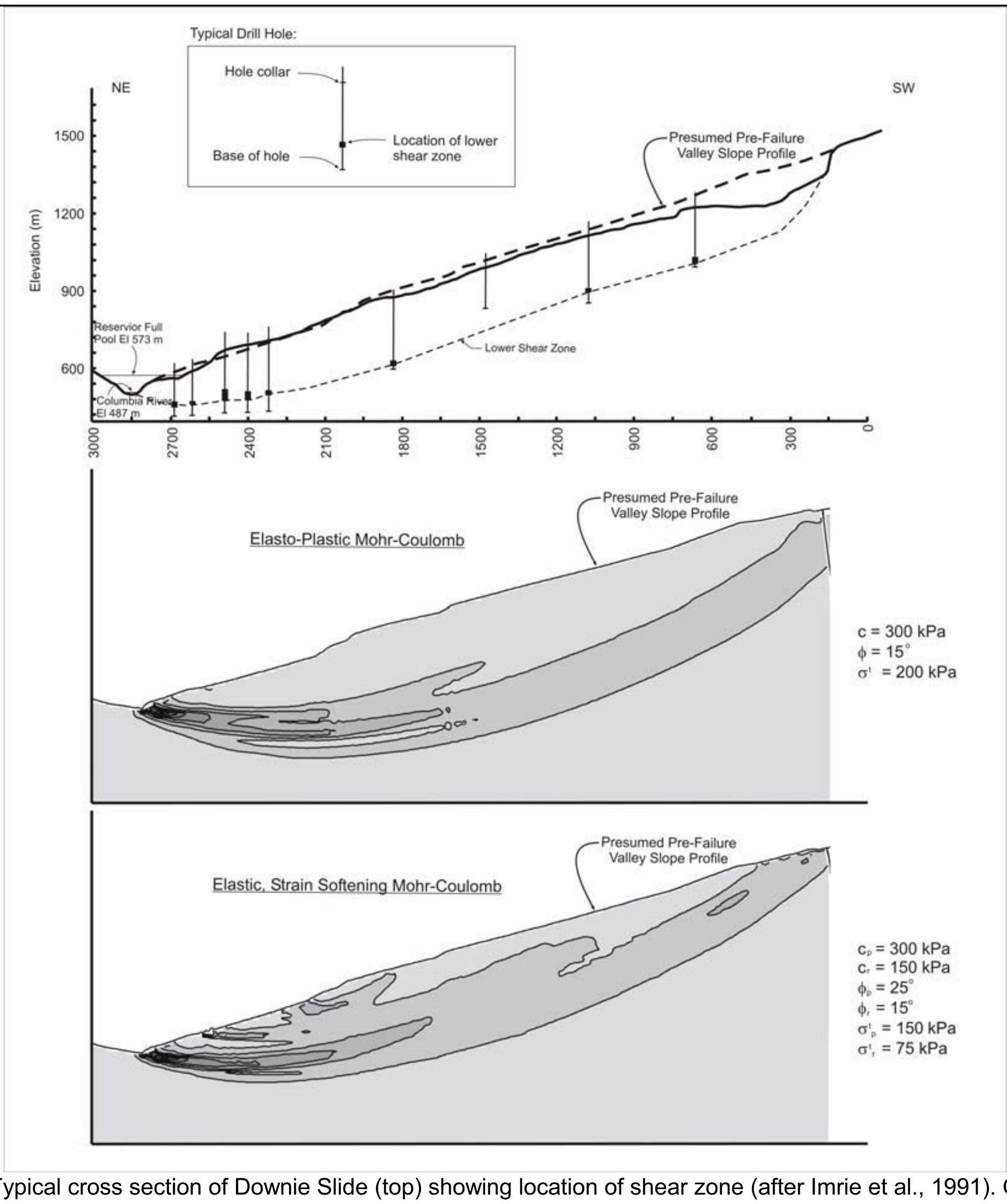

Figure 5. Typical cross section of Downie Slide (top) showing location of shear zone (after Imrie et al., 1991). Output from finite difference models using the elasto-plastic M-C (middle) and elastic, strain softening M-C (bottom) constitutive relations. Contours represent shear strain increments at intervals of 1x10^{-1}.

due to the fact that the default tensile strength values in FLAC are set to 0 kPa immediately after the peak tensile strength is reached – therefore simulating a brittle response. When non-zero tensile strengths were implemented, the computer program reached equilibrium, thereby allowing an assessment of the effect of other material inputs and the constitutive model. Similarly, if the cohesion is set to 0 kPa, failure occurs in unexpected regions of the grid, causing errors within the computer program.

The development of significant shear strains occurred for low friction values (particularly 15°), and all associated cohesion values. At slightly higher values (22.5°), localization of shear strains occurred only for cohesion values of 100 and 200 kPa. Higher values of cohesion at similar levels of friction allowed for local developments of shear strain, however, the model came to equilibrium before large-scale bands occurred.

Visual calibration for the elasto-plastic M-C constitutive model (Figure 5) tells us that this relation is not representative of the material behaviour observed within the Columbia River Valley. The model failure surface in this case, or region in which shear strains are developing, generates a large semicircular failure surface which extends much deeper into the ground than the failure surface location found through borehole investigations and monitoring.

5. ELASTIC, STRAIN SOFTENING MODEL

Intuitively, the degradation from an intact gneissic rock mass to a shear zone must be a strain softening process. Thus, the elastic, strain softening (more appropriately described as strain weakening) Mohr-Coulomb (M-C) constitutive relation (Figure 4b) was implemented next to determine the effect of strain propagation as a function of stress. The elastic strain variables in this model are similar to the available parameters within the elasto-plastic M-C constitutive model. For plastic strains, however, a gradual reduction in strength was implemented. The input values for the parametric analyses can be seen in Table 2.

Development of failure planes, either as indicated by yielded elements or accumulation of shear strains, began in the elasto-plastic M-C analyses at $\phi = 22.5^{\circ}$, and $\phi = 15^{\circ}$ for all cohesion values. The results from the elasto-plastic M-C analysis provided the basis for further constraining the range of properties for the elastic, strain softening M-C models. In particular, the peak and residual friction values that best stimulate the initiation and propagation of failure were selected. Similarly, peak cohesion values of 200 kPa and 300 kPa were chosen based on the previous elasto-plastic output. For residual cohesion, however, values were chosen as fractions of the peak in exponentially increasing functions as shown above. A tensile peak strength was assumed from typical tension cut-off limits for an elasto-plastic M-C material, and residual tensile strength values were implemented to determine the effects of residual tensile strength values, instead of an immediate loss of strength, as demonstrated in the previous analyses.

Table 2. Rock mass values employed in elastic, strain softening analyses.

Property	Value
Bulk Modulus, K (GPa)[1]	1.852
Shear Modulus, G (GPa)[1]	1.754
Density, ρ (N/m^3)[1]	2700
Dilation Angle, ψ[1]	0°
Friction Angle Peak, ϕ_p:	25° and 30°
Friction Angle Residual, ϕ_r:	15° and 20°
Cohesion Peak, c_p (kPa):	200 and 300
Cohesion Res., c_r (kPa):	$0.01c_p$, $0.05c_p$, $0.1c_p$, and $0.5c_p$
Tensile Peak, σ^t_p (kPa):	$0.5c_p$ and $1c_p$
Tensile Residual, σ^t_r (kPa):	$0.1\sigma^t_p$ and $0.5\sigma^t_p$

[1]represents values that were not varied parametrically

The results obtained using the elastic, strain softening M-C relation show that, for lower values of residual cohesion, the program was only able to simulate one third to three quarters of the stages of glacial retreat before unexpected termination of the program resulted due to grid errors. This was true for c_r values of $0.01c_p$, $0.05c_p$, and $0.1c_p$ (corresponding to values of 2, 10, and 20 kPa, or 3, 15, and 30 kPa, depending on the peak cohesion value). As values increased to $0.5c_p$ the program was able to fully simulate glacial retreat and to allow for further movements.

Interpretations on how the tensile strength affected the models could only be made if the program completed the deglaciation stages (i.e. for $c_r = 0.5\,c_p$). In some instances after complete glacial retreat, a single finite difference node in zones of tensile failure moved orders of magnitude further than adjacent nodes, as was seen during the modelling using the elasto-plastic M-C constitutive law. This occurred more frequently when the residual tensile strength was one tenth of the peak tensile strength, however, it was not uncommon in some runs for which $\sigma^t_r = 0.5\sigma^t_p$.

The residual friction parameter used in the analyses, however, strongly affected the model response. The results of a peak/residual combination (with various levels of tension and cohesion) of 25°/15° are comparable to those of 30°/15°. Likewise, results for a combination of 25°/20° are like those of 30°/20°. At the lower residual values, in runs that reached full glacial retreat, more substantial localization of shear banding, element yielding, and movement were observed, as would be expected.

Visual calibration for the elastic, strain softening M-C constitutive model (Figure 5) showed a much stronger correlation between regions of shear strain accumulation and the location of the measured shear zones within the slide mass than did the elasto-plastic M-C model. The failure region modelled is still more circular than that seen at Downie Slide, so the next stages of work will include

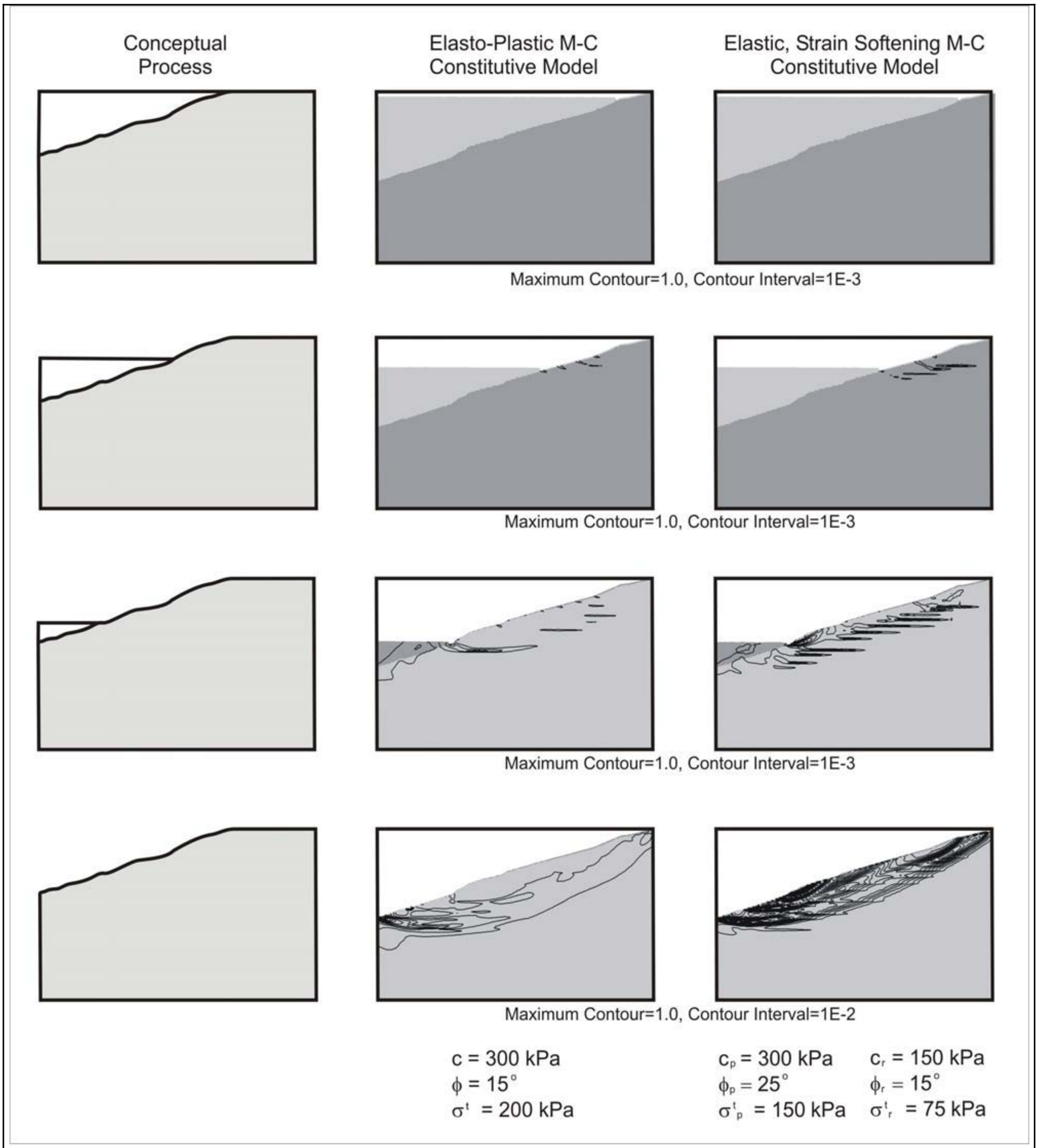

Figure 6. Comparison of shear strain increments for the finite difference model at different stages of deglaciation using elasto-plastic M-C and elastic, strain softening M-C constitutive relations. Note varying contour scales and the increased grid dependency for early shear propogation in the elastic, strain softening constitutive model.

implementation of ubiquitous joints into the elastic, strain softening model to identify the dependence of movement on the slope parallel foliations, seams, and interbedding present at the site.

6. DISCUSSION

Replicating the geologic history of this site is a critical step in the process of generating a realistic, calibrated numerical model of Downie Slide. Figure 6 shows the development of shear strains at different stages of deglaciation within the finite difference models. These shear strain contours, beginning at the ice/rock interface, appear to condition the slope for the development of an overall shear plane through progressive failure. In the elastic, strain softening M-C runs, however, these contours extend in a grid dependant manner as shown by the horizontal contours in the plots given in the third row of Figure 6. These strain contours are an expected result of stress relief and minor failure due to the effects of deglaciation. In the field, stress relief characteristics were observed to be parallel to the ground surface, so the horizontal contour orientations are considered to be not physically realistic. An attempt at minimizing this grid dependency by further randomizing the finite difference grid was instituted; however, any further randomization caused grid generation problems due to nodes being located in close proximity to the ground surface.

In addition to the contours generated by the grid dependency, it can be seen that the elastic, strain softening M-C model allows for more localized propagation of strains. Since the strains are localized in these high concentration areas, the model is able to develop a failure surface at shallower depths than in an elasto-plastic M-C relation. It remains to be seen how ubiquitous joints may affect the shape of the overall failure planes, however, it is expected that this addition will allow the model to react to the structural control of the rocks as seen in the field.

7. CONCLUSIONS AND FUTURE WORK

The outlined methodology is useful for slope stability studies of landslides where only portions of the required parameters for finite difference analyses are available. In this framework, geological understanding of the site, parametric analyses, and constitutive relation trial and error have provided output images used to visually calibrate the model against observed movements in the field, as well as to understand the influence of geological processes on the subsequent behaviour of the rock mass.

The result of this preliminary calibration has provided models that show a reasonable similarity to the mechanisms and deformations observed in the actual slope. This preliminarily calibrated model (proper constitutive law and focused range of parameters) can now be used for forecasting the potential destabilizing influence of external mechanisms.

Future work will involve testing a ubiquitous joint constitutive relation as well as fine tuning the model of Downie Slide by further calibrating the model based on the movements recorded by the extensive array of instruments within the slide. This fine-tuned model will then be used to examine the potential influence of changes in groundwater levels on the slide movement rate, and to generate preliminary rules for implementation into the DSS framework. The rules will include acceptable rates of slope movement, measured both on individual instruments and from the network of instrumentation data, and will provide additional insight and information for those monitoring the stability of the slide on a regular basis.

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