Development and calibration of numerical models for investigating trigger scenarios and mitigation techniques for massive landslide hazard management.

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ABSTRACT

Landslide hazard management at the Downie and Beauregard landslides is achieved by continuous monitoring and analyses of slope behaviour. These massive instabilities have extensive histories of slope monitoring and observational assessment and, in both cases, detailed investigations of geology, geomorphology and hydrogeology. Based on field data sophisticated three-dimensional numerical models have been developed to reproduced observed slope behaviour. This paper reviews the model calibration process which has improved the understanding of geomechanical conditions controlling slope kinematics. Calibrated models are used in ongoing research into how trigger scenarios may accelerate deformations at Downie and the effectiveness of proposed slope drainage at Beauregard.

RÉSUMÉ

L'administration des dangers aux glissements de terrains Downie et Beauregard est réaliser avec un système de surveillance continuelle et les analyses du mouvement de terrain. Ces blocs massives ont eu une programme de surveillance du mouvement de terrain et l'évaluation observationnelle historique extensive et en chaque cas, des investigations de la géologie, la géomorphie et la hydrogéologie. Après les données du domaine, des modèles numériques sophistiqués à trois dimensions ont été développé pour reproduire les mécanismes observés du terrain. Cet article revue le système de calibration du modèle qui avais aidé a mieux comprendre les conditions géomechaniques contrôlant les mécaniques du mouvement de terrain. Les modèles calibrés sont utilisés dans la recherche en cours expliquant comment les déclanchements de scenario peuvent accélérer la déformation à Downie et l'efficacité d'un système de drainage de terrain proposé à Beauregard.

1 INTRODUCTION

The Downie and Beauregard landslides are two massive, slow moving slope instabilities which are of concern to dam and reservoir hazard management. Downie is located on the west bank of the Revelstoke Reservoir approximately 60 km upstream from the Revelstoke Dam in British Columbia, Canada. Beauregard is located in northwest Italy and impinges on the left abutment of the Beauregard Dam. Given the physical scale and complexity of these landslides the complete arrest of slope movement is impossible. Therefore, continuous monitoring and analyses of slope behaviour play major roles in landslide hazard management. Slope behaviour analyses require understanding of the geomechanical factors controlling slope kinematics. These factors, including slope geometry, shear zone characteristics, material strength, and groundwater conditions, are heterogeneous across the extent of a landslide mass and are temporally variable.

Both the Downie and Beauregard landslides have extensive histories of slope monitoring and observational assessment. Records of these histories allow for forensic analyses of spatially discriminated slope deformations and the response of displacement rates to groundwater fluctuations. Numerical models have been developed for each landslide and are calibrated to reproduce deformation patterns observed in field data. This paper reviews this calibration process which has improved the understanding of geomechanical conditions controlling slope kinematics. Ongoing research uses the trained models to test how trigger scenarios may accelerate deformations at Downie and investigate the design and effectiveness of engineered mitigation techniques such as slope drainage at Beauregard.

2 CASE STUDIES

In both cases, detailed site investigations have been completed including studies of site specific geology, geomorphology and hydrogeology, in addition to analyses of slope monitoring data.

2.1 Downie

Downie is located on the west bank of the Revelstoke Reservoir in British Columbia, Canada (Figure 1). It is, in accordance with the Cruden and Varnes (1996) classification scheme, a massive, active, composite, extremely slow moving rockslide. This instability was first recognized by the British Columbia Hydro and Power Authority prior to dam construction. Understanding the hazard posed to reservoir and dam safety a monitoring network has been established and an extensive drainage system has been development for hazard mitigation.

The landslide volume is estimated to exceed 1.5 billion cubic meters, this instability measures approximately 2400 m along the toe and 3300 m from toe to headscarp with an estimated maximum thickness of 245 m (Enegren and Imrie 1996). The rockmass is highly fractured metasedimentary sequence of schists, gneisses and quartzites (Imrie et al. 1991). Landslide shear zones follow the well developed mica foliation which dips towards the river valley at about 20°. Three joint sets occur at Downie, one is sub-parallel to foliation and two are sub-vertical dipping roughly east and north. Multiple fold generations are evidence of poly-phase regional deformation.

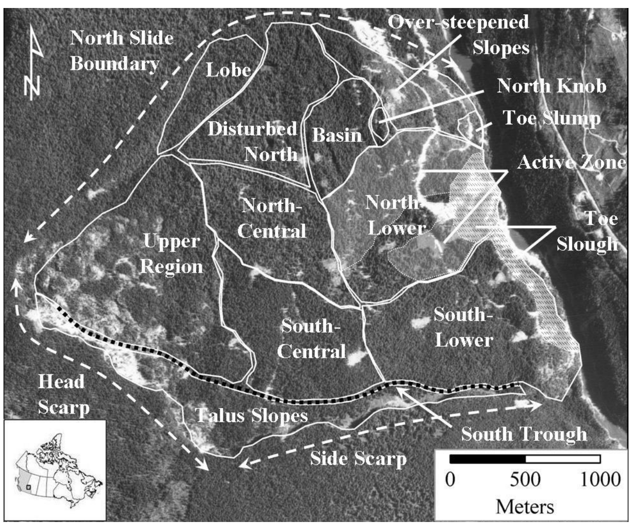

Figure 1: Landslide zones identified at Downie based on morphological features and spatially discriminated slope behaviour and failure mechanisms, (inset) location of Downie in southeastern British Columbia.

The modern Downie Landslide features a number of zones (Figure 1) which have been identified based on morphological features and spatially discriminated slope behaviour and failure mechanisms (Kalenchuk et al. 2010a). The main landslide mass is made up of the upper, central and lower regions with secondary instabilities to the south and north, including the talus slopes, the lobe, the disturbed north zone, the basin, the north knob, the over-steepened slopes and the toe slump. The upper portion of the slope is dominated by retrogressive failure and, with the exception of localized slump and slough features near the toe, this region shows the highest rates of deformation. Translational failure occurs through the central portion of the slide which is the slowest moving region. Rotational failure occurs at the toe where the basal shear zone crosscuts the foliation to outcrop in the river valley. Rates of deformation near the toe are moderate relative to the entire slide mass. A comparatively active zone is evident through the north lower region. Figure 2 illustrates a contour plot of displacement rate standard deviation from the mean, high deformation rates associated with localized slumps and sloughs along the toe are not included in this plot as these surficial features are not representative of the overall slope behaviour.

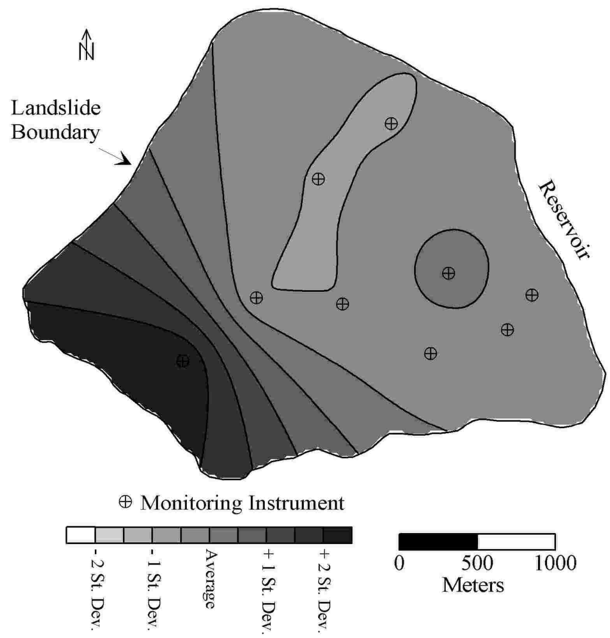

Figure 2: Downie Slide surficial displacement rate standard deviation from the mean slope velocity (modified after Kalenchuk et al. 2010a)

2.2 Beauregard

Located in the Aosta Valley (Dora di Valgrisenche River) in northwest Italy (Figure 3), the Beauregard Landslide is an extremely slow moving, deep-seated gravitational slope deformation (DSGSD). Beauregard impinges the left abutment of the Beauregard Dam; it was first recognized in the 1960s during initial filling of the Beauregard Reservoir. When accelerated slope movements were observed during reservoir filling, restrictions were placed on the reservoir capacity by the Italian Dam Authority. Designed to operate at 1770 m a.s.l., the reservoir is now permitted to operate at 1705 m a.s.l., with 1710 m a.s.l. as a maximum during flood periods (Barla et al., 2006).

Concerns of dam integrity stem from observed closure of the arch in response to continual loading of the abutment by the slope instability. In response to safety and operational concerns a recent site investigation was initiated in 2002 aiming to improve understanding the

DSGSD and the interaction of the slope instability with the dam. This has comprised geological, geomorphological, hydrological and geotechnical studies involving in situ and laboratory testing, geophysical seismic investigations and slope deformation and groundwater monitoring.

This massive landslide is approximately 1700 m wide and 2400 m from toe to headscarp; it extends from 1700 to 3200 m a.s.l. and has an estimated maximum thickness of 260 m (Miller et al. 2008). The rockmass is fractured gneiss and micaschists, with a foliation dipping 23° to 28° towards the valley. The basal shear zone, which follows this foliation, features sheared and crushed rock locally reduced to soil like material with silt and clay (Barla et al. 2006). Structural features are predominantly steeply dipping joints and shears which strike valley parallel. Minor jointing and shears are roughly orthogonal to these prominent features (Barla et al. 2006).

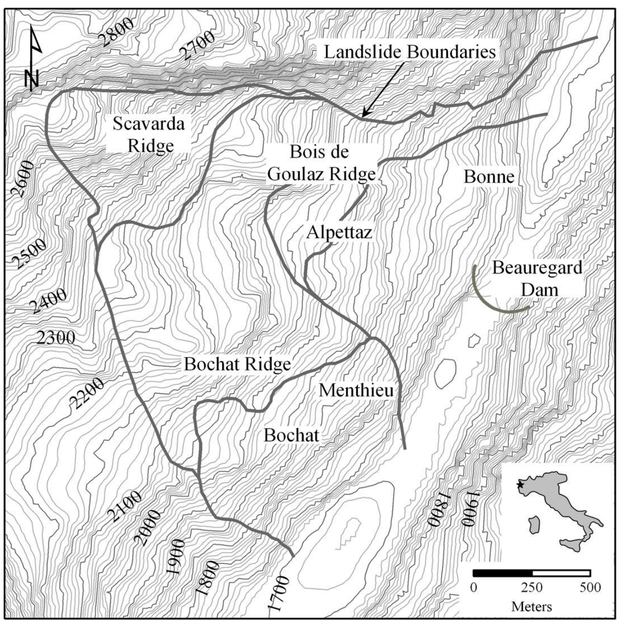

Figure 3: The Beauregard Landslide, inset shows location in the Aosta Valley (Dora di Valgrisenche River) in NW Italy. The landslide has been subdivided into a number of zones bound by the illustrated boundaries based on morphological features (Kalenchuk et al. 2010b).

Beauregard is bound by a prominent scarp to the west and north, and by less obvious trough features to the south. Internal scarps, ridges and troughs, open tension cracks and trenches dominate the landslide morphology. A number of landslide regions, delineated by the landslide boundaries illustrated in Figure 3, have been identified by morphological features and the location of shear zones identified in seismic profiles. The upper extents of the landslide features highly fractured and weathered rockmass. The Scavarda Ridge is a large mass which has broken away from the headscarp (Barla et al. 2009). Below this ridge localized toppling failure and rockfalls have contributed to talus accumulations. Two ridges occur through the central portion of the slide, Bois de Goulaz Ridge and Bochat Ridge. Tension features occur upslope from both. The lower region of the landslide, bound to the west by a well developed scarp near Alpettaz, features numerous minor scarps and counter-scarps striking valley parallel (Barla et al. 2009). Figure 4 illustrates Beauregard deformation rate standard deviation from the mean (Figure 4). The highest deformation rates occur through the upper portion of the slide with slower rates through the central region, moderate rates along the central and southern toe and the slowest rates at the north toe.

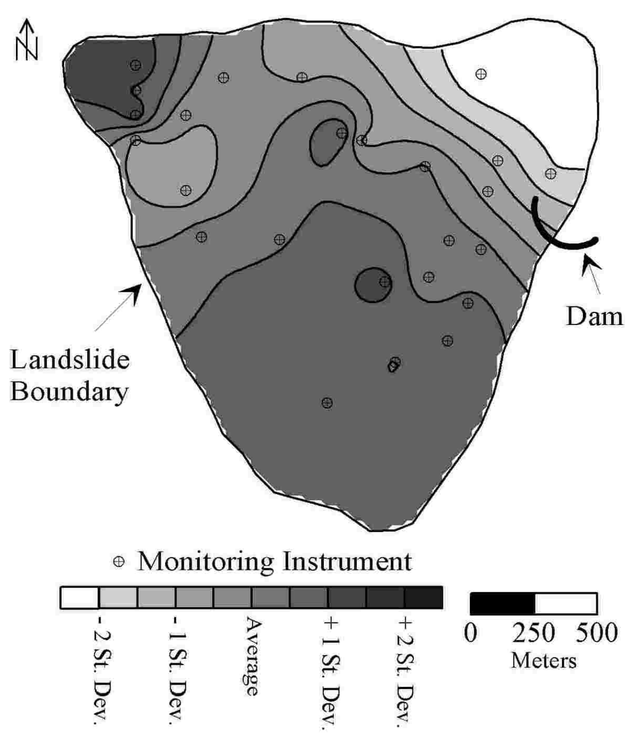

Figure 4: Beauregard displacement rate standard deviation from the mean (modified after Kalenchuk et al. 2010b).

3 NUMERICAL MODELLING

Three-dimensional numerical models have been developed and calibrated to reproduce observed slope behaviour for both case studies. The mixed continuum-discontinuum code 3DEC (3-Dimensional Distinct Element Code) (Itasca Consulting Group, Inc. Minneapolis, Minnesota, 2003) is used for numerical modelling. The landslide mass and in situ material below the landslide are defined as continuum materials and the Mohr-Coulomb failure criterion is applied to them. Material properties have been assigned to represent reasonable values for each site specific geological setting, with the exception of cohesion and tensile strength for the in situ material which are assigned values of 1 GPa and 100 MPa respectively. These unrealistically high values ensure that no failure occurs outside of the landslide boundaries; a reasonable condition given that the scope of this modeling is to study the behaviour of existing landslides rather than the propagation of new instability. Both the in situ and disturbed materials are assigned zero dilatancy.

The landslide mass and the in situ material interact along discontinuum joint elements which define the landslide shear surfaces. These are controlled by the Coulomb-slip constitutive model (Itasca Consulting Group, Inc. 2003). In the Downie models joint elements are perfectly plastic as the shear zone has achieved residual strength. In the Beauregard models the lower portion of the slope is perfectly plastic while the upper portion is hypothesised to behave brittle. Discontinuities are assigned strength parameters derived from laboratory test results and model sensitivity testing, joint dilation is assumed to be zero and base case shear and normal stiffness values are set at 50 and 100 MPa/m, respectively. Figures 5 and 6 summarize the material properties for Downie and Beauregard respectively.

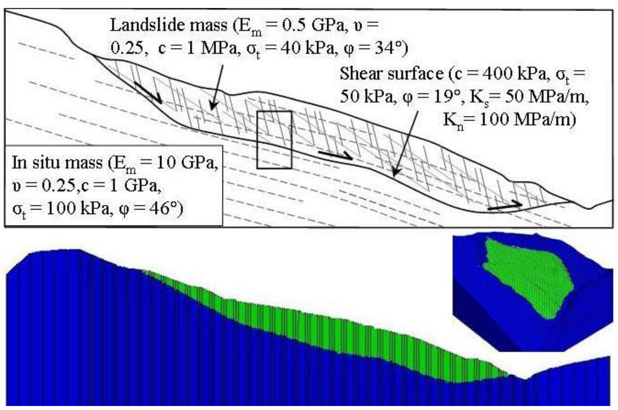

Figure 5: (top) Material properties utilized for 3DEC simulations of Downie (bottom) typical cross section through the model (inset) isotropic view of the model looking NW (modified after Kalenchuk et al. 2010c).

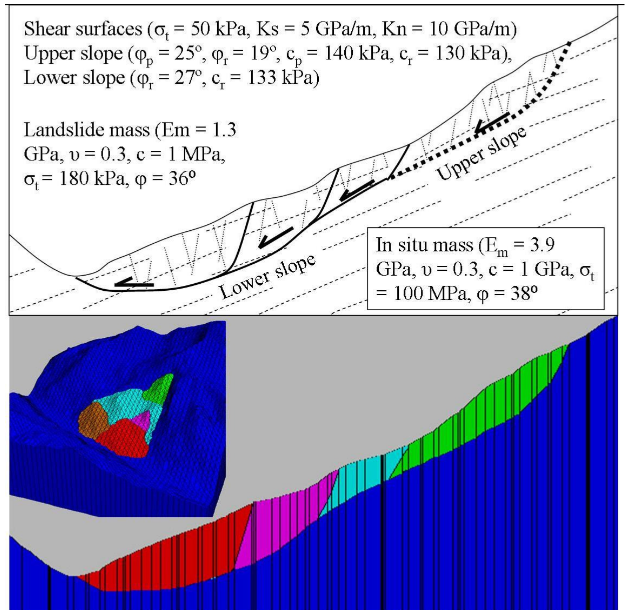

Figure 6: (top) Material properties utilized for 3DEC simulations of Beauregard (bottom) typical cross section through the model (inset) isotropic view of the model looking SW (modified after Kalenchuk et al. 2010b)

4 MODEL CALIBRATION

The calibration process for landslide models varies between the two case studies, because due to site specific field investigation programs each landslide has different information available. At Downie an impressive number of boreholes have been cored and logged providing information pertaining to the location of the basal slip surface, spatial variance in the thickness of this shear zone, and the occurrence of secondary shears within the landslide mass. At Beauregard three seismic profiles have been completed helping to define the shear zone geometries, only two boreholes have been cored and logged providing data too sparse to reasonably define variance in shear zone thickness, and no information is available pertaining to secondary shears within the landslide mass. Significantly more data from laboratory testing of material properties is available for this study from Beauregard than from Downie. This data provides a basis for assigning material properties to Beauregard models, and some understanding of how these properties vary spatially. Material properties for Downie have been derived from typical values for the geological conditions. Landslide zones have been interpreted for both Downie and Beauregard. Zoning at Downie has been defined by studying spatial variance in morphological features and failure mechanisms. Zones at Beauregard are identified only by morphological features.

4.1 Downie

The calibration process for Downie models has tested how the three-dimensional shear zone geometry, spatial variance in shear zone stiffness as a function of zone thickness, the inclusion of internal shears and the interaction between landslide zones influence slope deformation patterns. Deformation rates, sampled on the topographic surface of the numerical models at the same location as field instruments, have been standardized in the same fashion as field data. This ensures field data, measured in mm/year, and model data, measured in mm/time step, can be directly compared. The ability of different models to reproduce field observations is statistically measured by R^2 values, defined by correlating standardized numerical and field data, and qualitatively visually comparing spatial patterns on the contour plots.

The location of the basal slip surface at Downie has been identified at 42 sub-surface data points (borehole intercepts) and the landslide boundary which marks the shear zone outcrop. From these data a number of geologically realistic shear zone geometries in addition to an over simplified bowl shaped geometry have been interpreted by Kalenchuk et al. (2009) (Figure 7), and applied to numerical simulations. All complex geometries perform well in comparison to the over simplified geometry which does not adequately reproduce observed deformation patterns. The best simulation of field data is achieved using the stepped surface interpreted by a minimum curvature algorithm (Kalenchuk et al. 2010c).

The thickness of the basal slip surface at Downie has considerable spatial variation, ranging from less than 2 m to more than 50 m (Figure 8). Using the stepped minimum curvature shear surface models further testing has looked at how spatial variance in shear zone normal and shear stiffness as a function of shear zone thickness influence deformation patterns. This is achieved by dividing the shear zone into three regions representing thin, average, and thick portions of the basal slip surface. Stiffness multipliers are then applied to the base case shear and normal stiffness, of 50 MPa/m and 100 MPa/m respectively. The ratio of stiffness multipliers (thin region:average region:thick region) is varied between 0.1:1:10 and 10:1:0.1, only those results for 0.2:1:5, 1:1:1 and 5:1:0.2 are illustrated here (Figure 8). It has been found that increasing shear zone stiffness in thin region and decreasing shear zone stiffness in thick regions improves the numerical reproduction of field data.

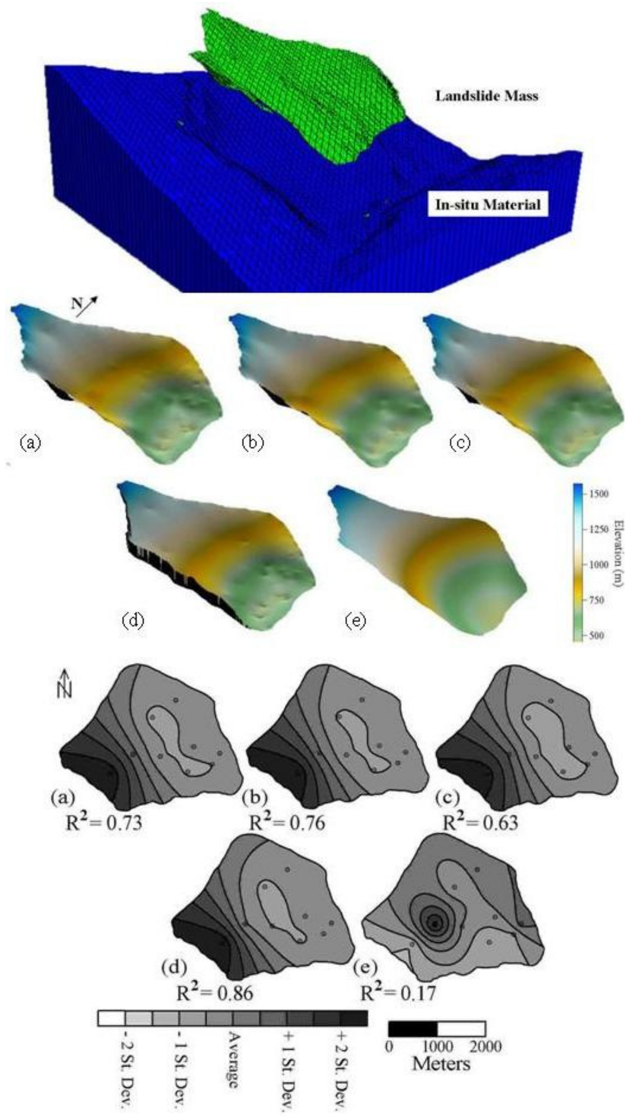

Figure 7: (top) Exploded view of a Downie numerical model. (middle) Different interpretations of shear zone geometry: (1) continuous (a. minimum curvature (smooth), b. kriging of a variogram model and c. the multiquadratic radial basis function), (2) stepped (d. minimum curvature (discontinuous)), and (3) simplified (e. the elliptical parabola). (bottom) Contour plots of displacement rate standard deviation from the mean.

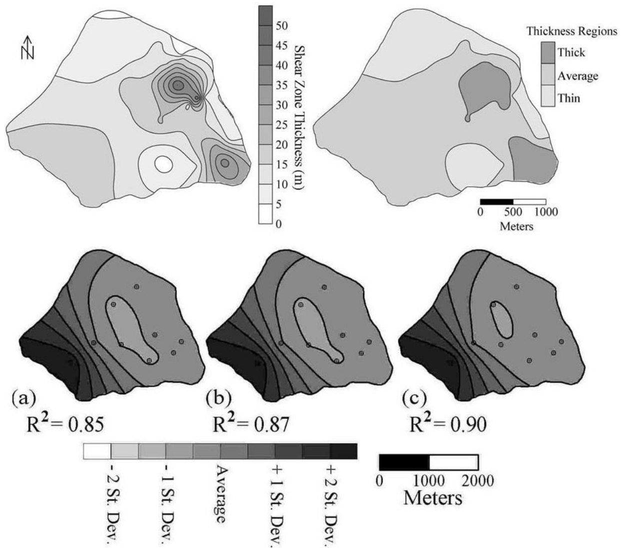

Figure 8: (top left) contour plot of the thickness of the basal slip surface at Downie, (top right) thin, average and thick regions are defined within the numerical models, (bottom) contour plots of displacement rate standard deviation from the mean taken from numerical models where the ratios of stiffness parameter multipliers are (a) 0.2:1:5 (b) 1:1:1 (c) 5:1:0.2.

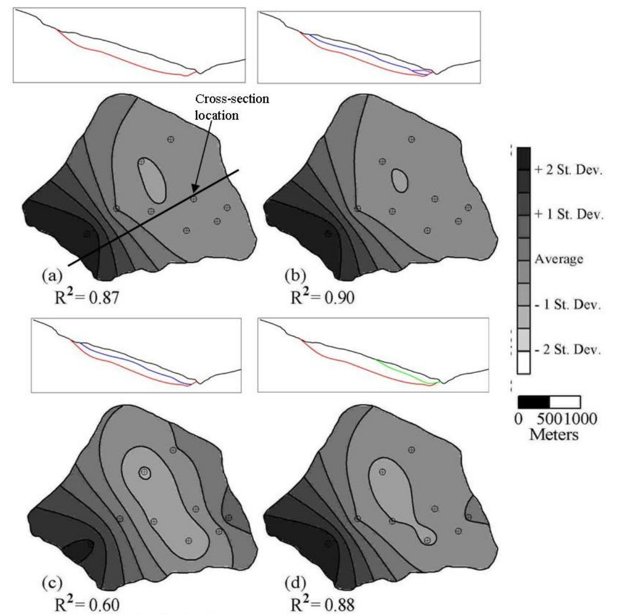

Figure 9: Contour plots of displacement rate standard deviation from the mean from four models with different assumptions of internal shears.

Internal shears are documented in borehole logs from Downie. While the occurrence of internal shears is known, it is difficult to assume the spatial continuity between these secondary features. Therefore, a number of interpretations of internal shears have been numerically tested. Figure 9 illustrates four models; (a) a monolithic mass with no internal shears, (b) one internal shear continuous across the entire landslide extend and a second internal shear near the toe, (c) one internal shear continuous across the entire landslide extent, (d) one internal shear continuous only through the active zone. The inclusion of secondary shear makes minor improvements to the simulation of observed slope behaviour. Based quantitatively on R^2 and qualitatively on visual inspection of slope deformation patterns, the inclusion of two continuous internal shears, or one internal shear confined to the active zone, produce the best results.

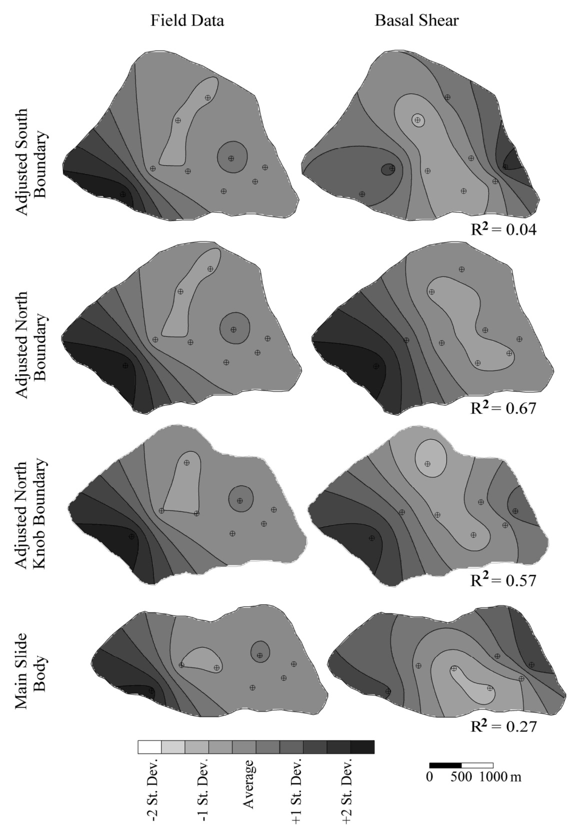

Figure 10: Numerical simulations of Downie taking into account different interpretations of the slide boundary as to incorporate various secondary instability regions (left) field data (right) model output.

The last series of calibration models for Downie looks at the interaction between primary and secondary failure zones. Figure 10 illustrates four models with different secondary zones included in the model; (1) the southern talus slopes are removed, (2) and (3) are two interpretations of the northern regions and (4) is a simulation of only the main landslide mass. When secondary instabilities are not included the simulated behaviour does not match field observations well. This indicates that important mechanical interactions are occurring between different regions of the slope. For instance, in reality the talus slopes, the destabilized north zone and the basin would generate some load acting on the main slide mass which is not accounted for numerically where hard boundaries are defined at the perimeter of the main instability.

4.2 Beauregard

Calibration of the Beauregard Landslide models has taken into account shear zone geometry, spatial variance in shear zone strength parameters and the interaction between landslide zones. Deformation rates have, again, been sampled on the modelled topographic surface at the same location as field instruments and are standardized for comparison to field data.

The three-dimensional geometry of the Beauregard basal slip surface has been interpreted from the shear zone location identified in three seismic profiles, two borehole intercepts and the landslide boundary. Based on minimum cross-validation error and visual assessment of spatial patterns a minimum curvature algorithm and a multiquadratic radial basis function were deemed best suited to the available data and geologically realistic. Figure 11 illustrates these geometries, which have been applied to numerical models. The minimum curvature geometry returns the highest R^2 values and produces the best representation of deformation patterns.

Using the minimum curvature basal slip surface geometry a more detailed investigation to shear zone strength parameters has been completed. Unlike Downie where spatial variance in shear zone thickness is well sampled by numerous boreholes, the shear zone thickness is only recorded for two boreholes intersecting the basal slip surface at Beauregard. Given this obvious data limitation it is impossible to interpret spatial variance in shear zone thickness across the extent of the entire instability. However, there is considerable laboratory testing data available to characterise the shear strength of various materials including: undisturbed shear zone samples (φ_r = 27°, c_r = 133 kPa) and schistose material (φ_p = 25°, φ_r = 19°, c_p = 140 kPa, c_r = 130 kPa). It has been hypothesised that the lower region of the landslide, where the shear zone is well developed, would have material properties similar to those samples taken from the shear zone, and at higher elevations, where failure is believed to be more brittle, material properties are thought to be closer to those measured along the schist foliations. A suite of numerical models have been run to test how simulated slope behaviour changes when the models are assigned a range of residual frictional values (25° to 29° for the lower portion of the slope and 17° to 21° for the upper portion). Figure 12 illustrates the modeling results; it has been concluded that a residual friction of 25° be applied to the lower slope with peak and residual friction equal to 25° and 19°, respectively, applied to the upper slope to optimize the simulation of field observations.

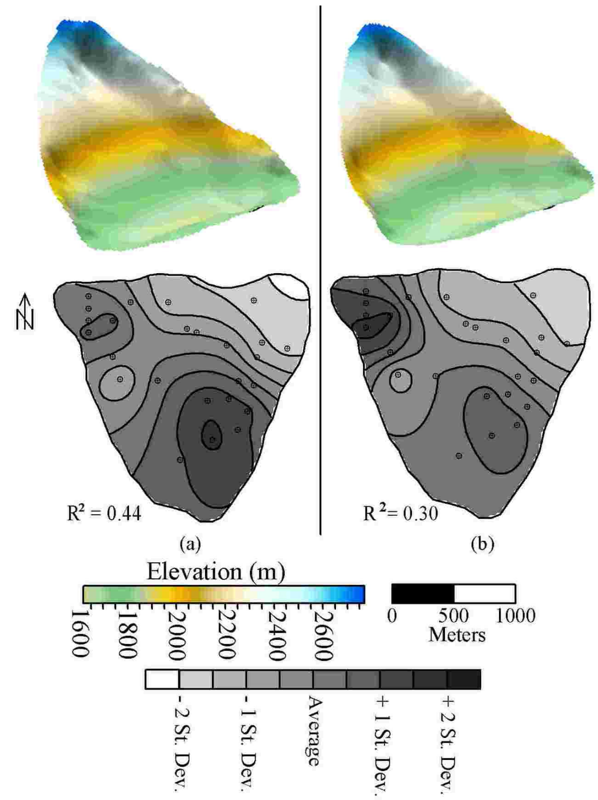

Figure 11: (top) Isotropic view and (bottom) contour plots of displacement rate standard deviation from the mean from numerical models with basal slip surface geometries defined by (a) a minimum curvature algorithm and (b) a multiquadratic radial basis function.

The final stage in calibration of the Beauregard models was to look at how the discrete specification of internal zones influences overall deformations. Figure 13 illustrates the base case landslide model with numerous zones and a simplified monolithic model. The zoned model produces better R^2 values and spatial deformation patterns.

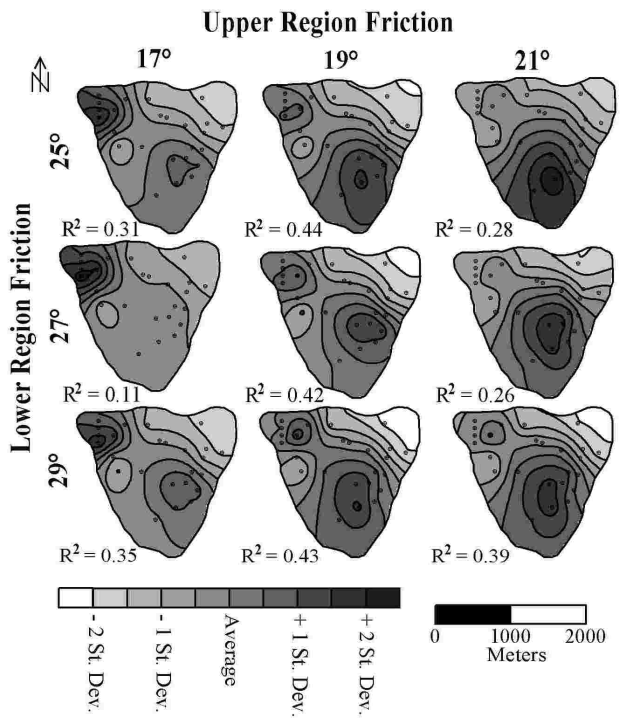

FIGURE 12: Contour plots of standardized deformation rates in numerical models with varying frictional strength in the upper and lower regions of Beauregard Landslide.

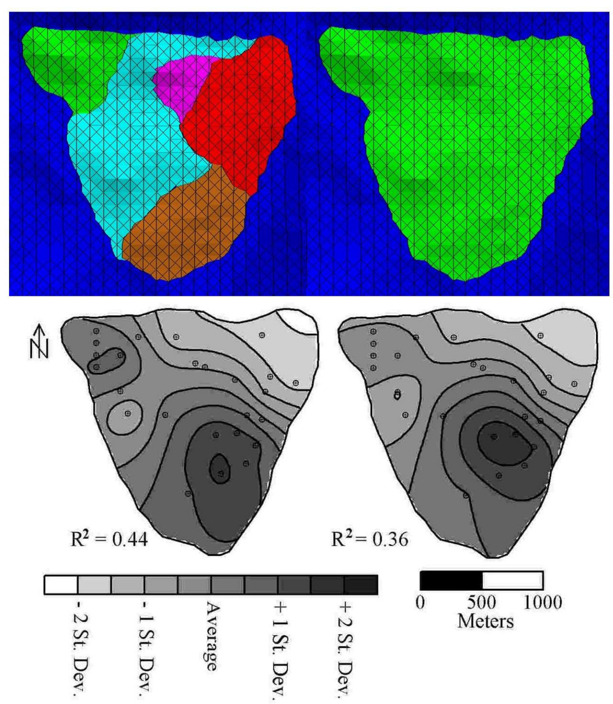

Figure 13: (top) plan view of numerical models with (left) discrete landslide zones and (right) a single monolithic mass. (bottom) contour plots of displacement rate standard deviation from the mean measured in models.

5 DISCUSSION

Calibration of the Downie and Beauregard numerical models has taken into account a number of factors influencing slope deformation patterns. Testing for Downie has demonstrated that numerical models with complex three-dimensional shear surface geometries improve the simulation of slope deformations when compared to oversimplified bowl shaped shear surface. Different interpolation algorithms have been used to develop multiple geometries and for both case studies the minimum curvature algorithm has provided geologically realistic geometry capable of achieving slope deformation patterns most comparable to field observations.

Spatial variance in shear zone strength parameters also plays an important role in discriminated slope deformation rates. At Downie, the shear zone thickness is well defined and numerical models have proven that as a shear zone becomes thinner the stiffness of that zone becomes, relatively, greater. Beauregard modelling has tested the shear zone frictional strength over a range inclusive of values recorded by laboratory testing. Frictional values lower than those returned by laboratory testing produce the best simulation of observed slope behaviour. This intuitive result is likely a reflection of laboratory tests overestimating rockmass conditions due to inherent scale effects.

Both case studies have taken into consideration the interaction between landslide zones. Numerical results have indicated that the simulation of a massive landslide can be improved by defining landslide regions; as done through inclusion of secondary shears at Downie and discretely defined zones at Beauregard. Downie modelling has also demonstrated that important mechanical interactions occur between primary and secondary landslide regions. It is therefore necessary to simulate the entire area of instability, rather than exclusively the main landslide mass. Loading that occurs between landslide regions is neglected when a specific zone is confined by a hard boundary.

6 SUMMARY

The complete arrest of slope movement in massive complex landslides is impossible and therefore, continuous monitoring and analyses of slope behaviour are key components in hazard management. This paper reviews the model calibration process which has improved the understanding of geomechanical conditions controlling slope kinematics at the Downie and Beauregard landslides. This modelling has demonstrated the necessity for rigorous development of sophisticated three-dimensional simulations. The reproduction of observed slope behaviour is improved with complex shear zone geometries, spatial variance in shear zone strength parameters and the discrete definition of landslide zones.

Using these calibrated models it is now possible to test trigger scenarios and engineer mitigation plans. For

Downie, testing is underway of a rapid reservoir drawdown scenario to examine how unloading of the toe while maintaining high pore pressures through the lower slope would influence stability. Continued modelling for Beauregard will assess the effectiveness of slope drainage as an engineered mitigation technique.

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