Multi-Dimensional Analysis of Large Complex Slope Instability: Case Study of Downie Slide, British Columbia, Canada

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ABSTRACT
Downie Slide is a massive, active, composite, extremely slow moving rockslide located on the Revelstoke Reservoir in British Columbia. It is 1.5 billion m^3, measuring 2400m along the river valley, 3300m from toe to headscarp and up to 245m thick. Significant contributions to the field of landslide geomechanics have been made by analyses of spatially and temporally discriminated slope deformations, and how these are controlled by complex geological and geotechnical factors. Downie research demonstrates the importance of delineating massive landslides into morphological regions in order to characterize global slope behaviour and identify localized events, which may or may not influence the overall slope deformation patterns. Massive slope instabilities do not behave as monolithic masses, rather, different landslide zones can display specific landslide processes occurring at variable rates of deformation. The global deformation of Downie is extremely slow moving; however localized regions of the slope incur moderate to high rates of movement. Complex deformation processes and composite failure mechanism are contributed to by topography, non-uniform shear surfaces, and heterogeneous rock mass and shear zone strength and stiffness characteristics. Further, from the analysis of temporal changes in landslide behaviour it has been clearly recognized that different regions of the slope respond differently to changing hydrogeological boundary conditions. Sophisticated three-dimensional numerical models have been developed and calibrated to study the Downie dynamics. These models have provided valuable insight into massive landslide geomechanics, as they have taken into account complex three-dimensional geometries, heterogeneous shear zone strength parameters, internal shear zones, the interaction of discrete landslide zones and the hydro-mechanical influence of piezometric fluctuations.

RÉSUMÉ
Downie Slide est un massif , actif, composite , extrêmement lent éboulement mobile situé sur le réservoir Revelstoke en Colombie-Britannique . Il est de 1,5 milliards de m3 , mesure 2400m le long de la vallée de la rivière , 3300m de la pointe au escarpement et jusqu'à 245m d'épaisseur. Des contributions importantes au domaine de la géomécanique de glissements de terrain ont été réalisés par des analyses de déformations de la pente spatialement et temporellement discriminés , et comment ceux-ci sont contrôlés par des facteurs géologiques et géotechniques complexes . Downie recherche démontre l'importance de la délimitation des glissements de terrain dans les régions morphologiques afin de caractériser le comportement global de la pente et identifier les événements localisés , qui peuvent ou peuvent ne pas influer sur les tendances générales de la déformation de la pente . Instabilités de pente massives ne se comportent pas comme des masses monolithiques , plutôt , différentes zones de glissements de terrain peuvent afficher des processus de glissements de terrain survenus spécifiques à des taux variables de déformation . La déformation globale de Downie est en mouvement extrêmement lent ; Toutefois régions localisées de la pente encourent modérée des taux élevés de mouvement . Processus de déformation complexes et mécanisme de rupture composite sont apportés par la topographie , les surfaces de cisaillement non uniformes , et de la masse de roche hétérogène et résistance à la zone de cisaillement et des caractéristiques de rigidité . En outre, à partir de l'analyse de l'évolution temporelle de comportement des glissements de terrain , il a été clairement reconnu que les différentes régions de la pente réagissent différemment à l'évolution des conditions aux limites hydrogéologiques . Modèles numériques en trois dimensions sophistiqués ont été développés et calibré pour étudier la dynamique Downie . Ces modèles ont fourni de précieux renseignements sur la géomécanique de glissements de terrain massifs , comme ils l'ont pris en compte des géométries complexes en trois dimensions , les paramètres de résistance de la zone de cisaillement hétérogènes , des zones de cisaillement internes , l'interaction des zones de glissement de terrain discrètes et l'influence hydro-mécanique des fluctuations piézométriques .

1 INTRODUCTION

Downie Slide, in its modern state, is a massive, active, composite, extremely slow moving rockslide (Kalenchuk et al., 2009). The modern mechanics of Downie Slide have been interpreted from more than 35 years of slide monitoring data, a detailed study of the physical landslide setting and sophisticated numerical models. This comprehensive assessment of landslide mechanics has drawn on an understanding of the geological, morphological, and hydrogeological setting and observations of slide behaviour through slope monitoring. Through this rigorous study, valuable insight has been gained about the geomechanical controls of massive landslide slope behaviour.

2 CASE STUDY

Downie Slide is situated on the west bank of the Revelstoke Reservoir in southeastern British Columbia, Canada. Mapping was initiated in 1956 during site investigation prior to reservoir development. Data from this early investigation has been supplemented by numerous subsequent studies (for example; Wheeler 1965, Jory 1974, BC Hydro 1974, 1976, Bourne et al. 1978, Bourne and Imrie 1981, Brown and Psutka 1980, Gerraghty and Lewis 1983), records of borehole geology logs and geological mapping of two drainage adits, site visits by the authors in 2008 and 2009, and LiDAR data acquired in 2009.

Slope behaviour has been tracked since the 1970s by surface survey monuments and inclinometers. This monitoring has included periods of baseline monitoring, slope drainage by boreholes drilled from two adits at the base of the slide, reservoir impoundment and subsequent drainage system maintenance campaigns.

Considerable advances in the geomechanical understanding of Downie Slide were made by Kalenchuk et al. (2012, 2013a, 2013b), by generating fully three-dimensional numerical simulations capable of accounting for complex shear surface geometries, multiple water tables, and spatial variation in shear zone material properties.

3 LANDSLIDE ZONING

Landslides are defined as composite, when different types of movement occur in different areas of the displaced mass (Cruden and Varnes 1996). To interpret landslide mechanics it is necessary to recognize whether different landslide zones exhibit variable behaviour. Figure 1 illustrates Downie Slide divided into zones with distinct morphological features and specific slope behaviour. These zones have been interpreted from LiDAR data, observations made during site visits by the authors in 2008 and 2009, and thorough analysis of slope monitoring data. This landslide zoning is based on observations of the modern Downie Slide; it is hypothesized that failure was initiated some 9000-10000 years ago during deglaciation (Piteau et al. 1978, Brown and Psutka 1980). Landslide mechanisms during early stages of the instability may have been quite different from those observed today.

3.1 Landslide Boundary

The most prominent morphological features at Downie Slide are the head scarp and side scarp (Figure 2). These sub-vertical faces reach up to approximately 120m in height. Their geometry and the blocky nature of the scarp faces are controlled by the jointing fabric. The north extent of the landslide is clearly visible in LiDAR imagery. The northeast alignment of this north boundary and the occurrence of streams which flow northeast past the landslide boundary may suggest some structural control on the lineament development.

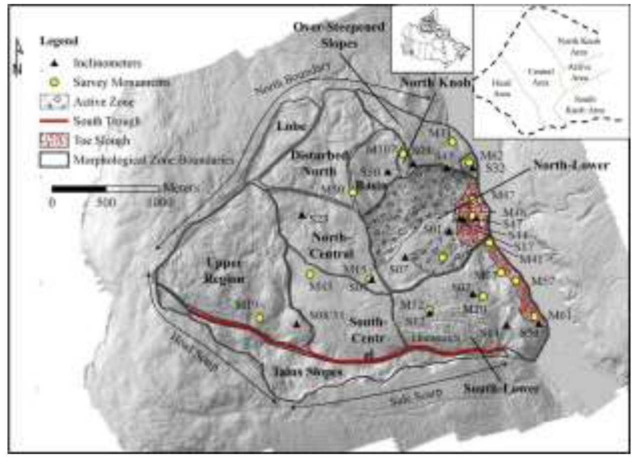

Figure 1: Aerial view of Downie Slide LiDAR data showing landslide zones.

3.2 Upper region

The Upper region is characterized by hummocky terrain made up of large, partially disturbed rock blocks, separated by extensional features which are littered with jumbled talus. Translational retrogressive failure is recognized in this region (Patton and Hodge 1975, Piteau et al.1978, Kalenchuk et al. 2013a). Large blocks are interpreted to have progressively broken off the scarp, thereby expanding the landslide footprint over time. Temporal variances in measured deformation rates in this region likely reflect individual blocks experiencing localized periods of activity and inactivity.

3.3 South Trough

The South Trough runs approximately parallel to the side and head scarps. It is a depression characterized by numerous internal scarps and tension cracks (Figure 3). The South Trough has been interpreted to mark the south boundary of the main landslide mass (Patton and Hodge 1975, Kalenchuk et al. 2013a). This interpretation corresponds well with findings summarized by Gerraghty and Lewis (1983) where drilling from one of two drainage adits developed on site prior to reservoir filling found an extremely fractured water bearing zone about 150 m north of the south scarp. Patton and Hodge (1975) interpreted from the position of the South Trough that total slide displacements are approximately 250 to 300m.

3.4 Talus Slopes

Between the South Trough and the scarps is an area of jumbled talus. These talus slopes have accumulated from gradual ravelling of the scarps. Fresh ravelling as well as talus slopes overgrown with old growth forest are observed on site (Figure 3), demonstrating that continued talus accumulation has been ongoing for a long time.

3.5 Central Region

The Central region of the landslide features gentle slopes overgrown by old growth forest. The South-Central area is relatively featureless with mature topography. The smooth nature of topography in this area may suggest that this portion of the slope has remained intact or that there has been little continued deformation since initial landslide activation and the early landslide features have since been worn away. A boundary between the north- and South-Central regions is marked by a subtle topographic break suggesting some degree of continued activity to the north where the terrain is slightly hummocky. Instrumentation from the Central region shows effectively negligible deformation (averaging less than 3mm/year) since reservoir filling. Inclinometer data suggests that deformation in the Central region is dominated by surficial movement, with only minor slip through the basal shear zone and internal slide deformation.

Figure 2: Downie Slide sidescarp and headscarp are geometrically controlled by joint structural trends.

Figure 3: (top) South Trough features including internal scarps and tension cracks. (bottom) Talus slopes overgrown by old growth forest. Inset photos show location of photograph.

Higher deformation rates are observed in the Upper region as compared to the Central region, implying that there should be some zone of accumulation at their boundary. Accumulation zones are generally characterized by evidence of thrusting, or bulging morphology. Such a zone has not been identified; however more detailed site investigation is required before drawing any firm conclusions. It may be speculated that there is no apparent zone of accumulation because early landslide activity may have initially extended only as far as the boundary between the upper and Central regions, leaving a zone of depletion which has since transitioned to a zone of accumulation as retrogressive blocks of the Upper region simply "catch-up".

3.6 Lower Region

The Lower Region features irregular terrain; depressions, crevices, internal scarps and fractures. The South-Lower area is a broad, over-steepened ridge marked by east-west trending lineaments roughly parallel to the South Trough and South Scarp (Figure 1). These features indicate north-south extension through the South-Lower region, however without detailed mapping it is difficult to conclude pure extension or translational extension with some down slope shearing component. The slight clockwise rotation in lineament orientation at lower elevations and bulging of the toe does suggest some down slope directed deformation.

Survey monuments in the South-Lower region have tracked deformation averaging 4.3 to 8.3mm/year since reservoir filling. Throughout the up-slope portion of the South-Lower region, deformation primarily occurs as creep through the landslide mass, while closer to the toe, discrete slip on the basal shear surface becomes more apparent in inclinometer data.

The north portion of the Lower region is the active landslide zone which is a depressional basin defined at the edges by scarp features and internally by hummocky, disturbed terrain. Two lobes, evident in LiDAR data (Figure 1), define areas of higher deformation rates. Survey data from the southern lobe of the Active Zone has measured movement rates averaging 19.2mm/year since reservoir filling. Unfortunately there are no instruments located in the northern lobe to measure activity in this area. Deformations along the basal shear and through the landslide mass are evident in all Active Zone inclinometers. The North-Lower region moves faster than the middle region and the boundary between these areas is marked by a zone of depletion with scarp features and sinkholes (Figure 4).

Figure 4: Depletion zone between the North–Lower region and the Central Region is characterized by tension cracks, internal scarps and sinkholes. Inset photos show location of photographs.

Along the reservoir, the Lower region features extensive toe sloughing. The extent of this surficial instability is clearly evident in LiDAR imagery (Figure 1). Survey monuments within this region typically return deformation rates varying between roughly 10 to 60 mm/yr. These high rates reflect surficial movement rather than overall landslide behaviour.

3.7 North Knob

The north knob is a prominent pinnacle of rock surrounded on all sides by extensional features and slopes covered in talus (Figure 5). This knob is likely a remnant morphological feature from early slide instability. Today, the north knob is predominantly inactive: a survey monument located at the peak of the knob has recorded negligible deformation, and extensional morphological features around the knob periphery suggest relaxation towards the surrounding topographic lows.

Figure 5: The north knob is marked by a (top) pinnacle or rock surrounded by (middle and lower) tension cracks and extensional features. Inset photos show location of photographs.

3.8 Over-Steepened Slopes

To the east and north of the north knob are over-steepened slopes (Figure 1). This region shows ongoing surficial deformation evident by curved tree trunks and surficial colluvium deposits. Morphological observations in this region show no prominent features to suggest modern, deep-seated displacements. A survey monument located in this area records slope parallel movement averaging 19.6 mm/year since reservoir filling.

3.9 Toe Slump

An active toe slump bounded by scarp features occurs at the landslide toe just north of the North-Lower zone

(Figure 1). This toe slump has anomalously high deformation rates (averaging 287 mm/yr since reservoir filling) making this zone the most active area of Downie Slide. The high rates observed here are not representative of the overall slide behaviour; inclinometer data has proven that movements are predominantly surficial deformation.

3.10 Basin

Upslope from the north knob is a basin region bounded by zones of depletion marked by scarps and sinkholes. To the east and west of the basin, ridge and trough morphology is observed (Figure 6) and east-west trending extensional features mark the north boundary. The basin itself slopes gently to the south, opening up, and draining into, the North-Lower zone. It is hypothesized that material from this region has gradually displaced south-southeast towards the active area, however there are no survey monuments present to provide magnitude and direction of deformation. Deformations within the basin are perceived to be negligible since reservoir filling.

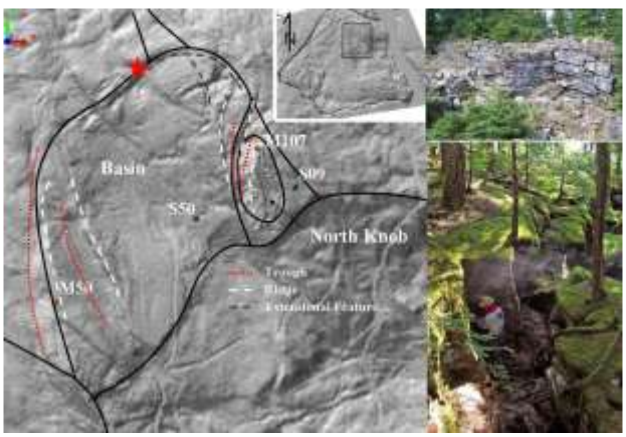

Figure 6: The basin is surrounded by extensional features to the west, north and east.

3.11 North Disturbed Zone

The North Disturbed zone (Figure 1) is interpreted as a region of secondary failure that may have initiated in response to the main instability to the south. Localized movement is directed northeast, east and southeast towards the over-steepened slopes, basin and main slide mass, respectively. This region is hummocky and terraced; modern deformations are believed to be surficial, however this is difficult to conclude without sub-surface deformation data.

3.12 Lobe

The Lobe (Figure 1) is interpreted to be a secondary failure. This region is bounded by two linear depressions, the upper portion of the Lobe does not feature any morphology to suggest landslide activity; however, the lower portion is terraced giving the impression of shallow failure though glacial deposits or ground cover rather than deep-seated failure through bedrock. This extension is likely initiated by the loss of material near the toe of the Lobe due to gradual movement of the over-steepened slopes. Northeast directed surficial movement is active today as evidenced by curved tree trunks.

4 LANDSLIDE BEHAVIOUR

4.1 Spatial Variance in Slope Deformations

Downie Slide is interpreted to be a massive, active complex, compound rockslide where the main landslide body can be divided into the Upper, Central, and Lower regions. Secondary instabilities on the landslide flanks include the Talus Slopes, the north destabilized zone, the Lobe and the Basin, as well as the over-steepened slopes and the toe slough area. These interpretations reflect the modern Downie Slide; it is difficult, if not impossible, to conclude how the initial slide behaved when instability began during deglaciation.

Failure mechanisms vary spatially across the slope. Translational sliding occurs, or has occurred at some point in landslide history, through the Central and Upper regions of the slide. Today, the Upper region shows retrogressive behaviour and the Central region shows negligible displacement rates. In the Lower landslide region the instability mechanism transitions from translational to rotational as the basal slip surface curves near the toe to outcrop in the valley. Here, particularly in the South-Lower region we see a transition from deformation distributed throughout the landslide mass to discrete slip on the basal slip surface. In the active Central toe region, most deformation occurs through the landslide mass. The most northerly part of the landslide toe (over-steepened slopes and toe slump zones) deformations are dominated by surficial instabilities, with minor slip on the basal shear surface and negligible deformation through the landslide mass. Sloughing along the reservoir toe acts to unload the landslide toe through erosional processes and may be an important control on slide behaviour, particularly in the Active Zone.

The northwest areas of Downie Slide, including the North Disturbed zone and the Lobe, are interpreted to be secondary surficial instabilities likely developed in response to the larger unstable mass to the south and east. The talus slopes along the southern portion of Downie Slide were generated by gradual scarp ravelling. The north knob is inactive and does not contribute to modern slope deformation.

When interpreting slide behaviour from instrumentation data it is important to bear in mind the specific deformation processes occurring at each instrument location. Survey monuments located in areas where surficial deformation has been recognized (for example, the toe slough, toe slump and over-steepened slopes) return elevated deformation rates that do not reflect the global slide displacement rates. Figure 7a demonstrates that when all survey monuments are considered on a contoured map of the overall slope behaviour there is an extremely fast zone near the northeast toe. This corresponds with the active toe slump. By removing that data from the global slope data set and reinterpreting overall slide behaviour, it becomes apparent (Figure 7b) that the Upper region of the slope and the active area in the Central toe move faster relative to the Central portion of the slide. Taking this one step further, the survey monuments located within the toe slough zone and on the over-steepened slopes can also be removed from the global data set to create a slope deformation plot that reflects the true global landslide behaviour (Figure 7c). With data influenced by localized behavior removed, the Active Zone is still evident in the North-Lower zone and the highest deformation rates are observed near the head scarp where failure is retrogressive. The central portion of the slide shows very little, to negligible, deformation rates; as would be expected by the lack of morphological features observed in this area.

4.2 Temporal Variance in Slope Behavior

Deformation monitoring data shows that the modern slope behaviour is largely controlled by changing groundwater boundary conditions. The groundwater setting at Downie Slide has been significantly impacted by the operation of the Revelstoke Reservoir. Groundwater levels have fluctuated over time in response to changing boundary conditions (Figure 8) resulting from the development of drainage infrastructure (1974-1982), toe inundation during reservoir filling (1983-1984) and gradual losses in drainage system capacity over the reservoir operating life (1985-2003).

Temporal changes to slide displacement rates, interpreted from survey monument data, are illustrated in Figure 9. Accelerations and decelerations less than ± 5 mm/year and annual displacement rates less than 5 mm/year are considered negligible, as such small magnitudes fall within the error margin of the measured data. Surficial instabilities, which are not representative of the global landslide behaviour, have been recognized near the landslide toe in the over-steepened slopes, toe slump and toe slough regions (Kalenchuk et al. 2013a). The responses of these surficial failures to changing groundwater boundary conditions vary considerably from the response of the main landslide body. While surficial behaviour does not contribute to global activity, it is important to recognize, and account for, these discrepancies.

Drainage development clearly shows decelerations across the entire landslide mass. Through the central and Lower regions of the slide this is a direct response to Lowered groundwater levels. Decelerated rates measured through the Upper region are attributed to localized behaviour of large blocks associated with the retrogressive development of this Upper region, rather than a direct response to drainage development. The most significant response to drainage development is observed throughout the Lower region of the main landslide body. Surficial deformation along the toe of the landslide show negligible changes in response to drainage development. Shallow instabilities are less influenced by water table drawdown because the water tables occur at depth below these surficial features and so pore pressures are not directly imposed on these areas of the rock mass.

The slope response to reservoir filling is spatially discriminated. Secondary surficial instabilities (the over-steepened slopes, the toe slump and toe slough regions) incurred considerable accelerations, however these were not reflective of the overall landslide behaviour. There are negligible changes through the Central and Lower regions of the main landslide mass with some minor decelerations through the central area of the main landslide body. These localized low magnitude decelerations are not interpreted to be in response to reservoir filling as this area of the slope is sufficiently far from the reservoir toe. The Upper region of the landslide does show some minor acceleration, this is interpreted as localized variation in activity rather than a direct response to reservoir filling. This area of the landslide is most influenced by infiltration and localized variation in activity may be related to precipitation and snow melt, however meteoric data has not been available for this analysis.

Over the operational life of the Revelstoke Reservoir, changes in landslide behaviour have been effectively negligible. Change in activity observed through the Upper region is again attributed to localized retrogressive behaviour. Minor accelerations are observed through the central portion of the Lower region (the Active Zone), this is probably in response to gradual losses of drainage capacity. Survey data suggests that the over-steepened slopes have decelerated following the accelerated response to initial toe inundation. With the exception of these minor, localized changes in deformation rate, the overall landslide behaviour has been steady-state over the operating life of the Revelstoke Reservoir.

5 NUMERICAL MODELLING

Extensive three-dimensional numerical modelling of the Downie Slide has been completed by Kalenchuk et al (2012, 2013a, 2013b). These models were rigorously calibrated to reproduce historical slope deformation data. The calibration process considered a number of geomechanical controls on slope behavior:

- Basal slip surface geometry.
- Spatial heterogeneity of geomechanical material properties, particularly the influence of inferred shear zone stiffness parameters.
- The role of internal shears on global slope behaviour.
- Interaction between primary and secondary landslide zones.
- Hydro-mechanical response to changing groundwater boundary conditions.

Through the testing of these factors it was found that the spatial discrepancies in the mode and rate of deformation at Downie Slide are predominantly influenced by irregular basal slip surface geometry. The landslide basal and internal slip surfaces are associated with foliation which has been gently warped and folded and so the shear surfaces have some degree of undulation. Numerical models proved the necessity of realistically representing shear surface geometry, rather than implementing oversimplified bowl shaped geometries.

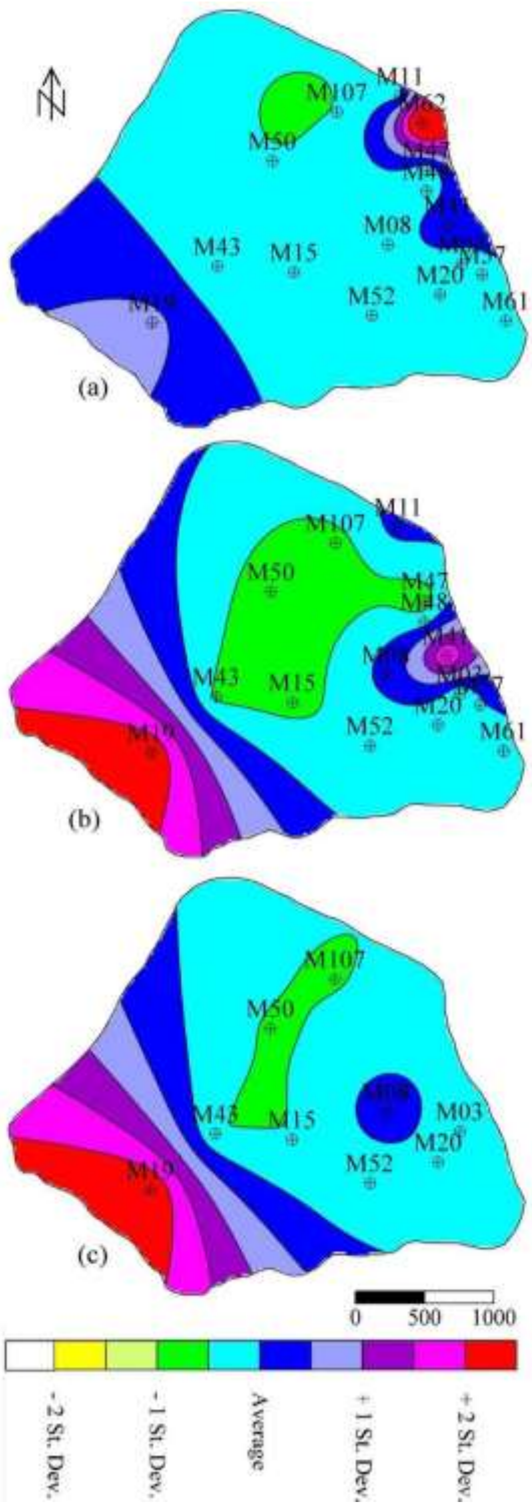

Figure 7: Contour plots of displacement rate standard deviation from the mean measured between 1990 and 2003; (a) all survey data utilized, (b) anomalous toe slump data is removed and (c) all data points with significant surficial deformation are removed to best demonstrate the true overall landslide behaviour (Kalenchuk et al., 2013a).

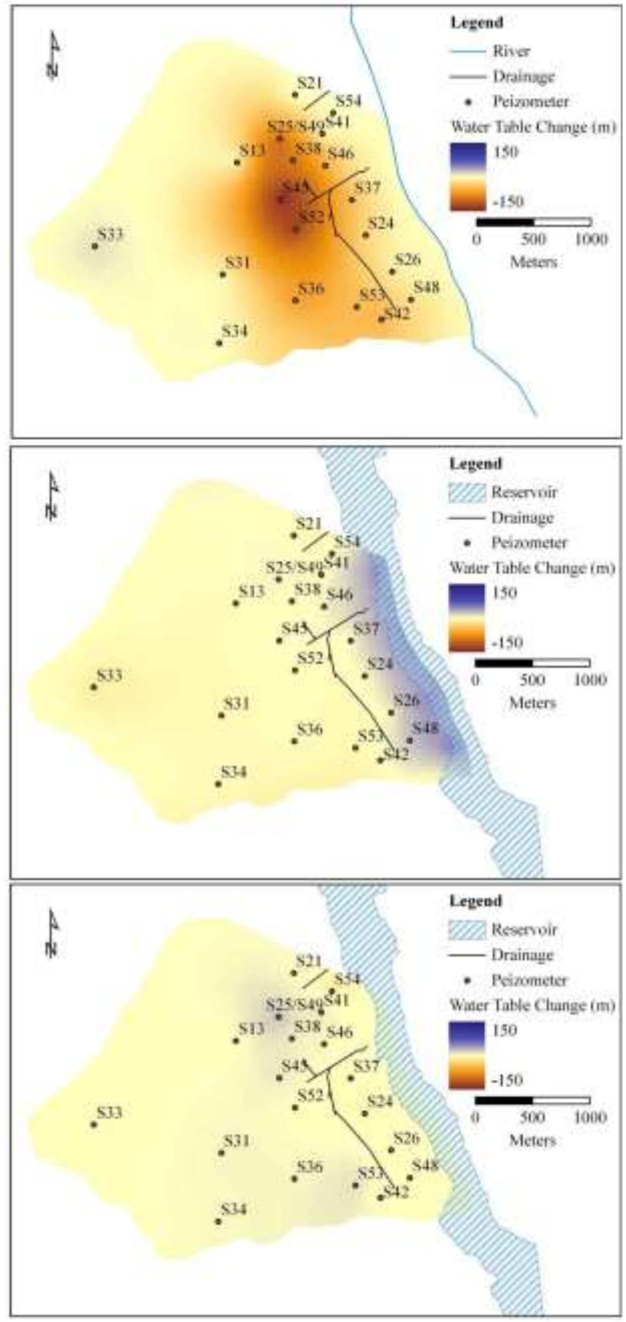

Figure 8: Groundwater fluctuations with changing boundary conditions at each stage of reservoir operations, including; (top) drainage development, (middle) reservoir filling, and (bottom) reduced drainage capacity (After Kalenchuk et al., 2013b).

Spatial variation in shear zone stiffness as a function of thickness also influences slope behaviour. The basal shear zone at Downie Slide ranges from less than 2 to nearly 50 m in thickness. By numerical model testing it has been concluded that thicker regions of a shear zone behave in a mechanically softer manner than thin regions. Heterogeneous shear zone stiffness induces localized stress concentrations and subsequent, local slip of discontinuity elements; contributing to complex three-dimensional slope deformation.

Three-dimensional numerical modelling was also successful in demonstrating that landslide behaviour is influenced by secondary shears within the landslide mass and the mechanical interactions between primary and secondary landslide zones.

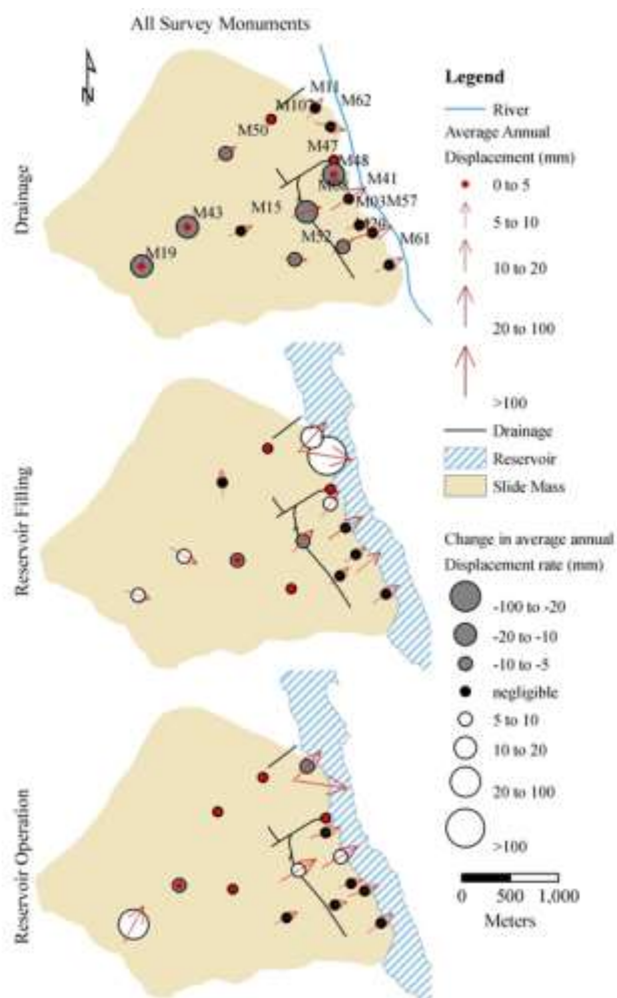

Figure 9: Deformation rates vary spatially and temporally, as different zones of the landslide show variable response to changing groundwater boundary conditions (Kalenchuk et al. 2013b).

6 SUMMARY

Downie Slide has been interpreted as a massive, complex-compound rockslide. Slope deformation is spatially discriminated where varying magnitude and direction of displacement rates have been observed across different regions of the landslide mass. A number of landslide zones have been defined based on interpretation of morphological features and a detailed assessment of spatial variation in slope behaviour. The main landslide mass, made up of the Upper, Central and Lower regions, features translational, rotational and retrogressive mechanisms. An Active Zone is found within the North-Lower region and a toe slough area extends along the reservoir shoreline. Secondary instabilities surround the main landslides, including the Talus Slopes, the Disturbed North zone, the lobe, the basin, the over-steepened slopes and the toe slump. The north knob is an inactive area, with negligible contribution to modern observations of overall landslide behaviour.

Downie Slide slope deformation is spatially discriminated; different regions of the landslide mass exhibit variable magnitude and direction of displacement rates. This case study has taken into consideration observed deformation from monitoring data, an understanding of the site morphology, geology and hydrogeology as well as the mechanics influencing individual landslide zones and the interaction between these zones. Conceptual interpretations of landslide mechanics have been tested by numerical modelling, which confirmed that the geomechancial mechanisms controlling massive slope instability include basal shear surface geometry, heterogeneous shear zone stiffness, internal shear zones and the interaction between primary and secondary landslide zones.

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REFERENCES

B.C. Hydro, 1974. Summary of 1973 Exploration Program. B.C. Hydro Engineering Hydroelectric Design Division. Report Serial No. 725.

B.C. Hydro (1976) Summary of 1974-1975 Exploration Program, Report number 744, June 1976.

Bourne, D.R., Imrie, A.S. and Wade, M.D., 1978. Downie Slide Investigations Report on 1976-1977 Field Work.. B.C. Hydro Hydroelectric Generation Projects Division. Report No. HE.C. 925.

Bourne, D.R. and Imrie, A.S., 1981. Downie Slide Investigations Report on 1981 Drilling Program. B.C. Hydro Hydroelectric Generation Projects Division. Report No. H 1469.

Brown, R.L. and Psutka, J.F., 1980. Structural and stratigraphic setting of the Downie Slide, Columbia River valley, British Columbia, Canadian Journal of Earth Sciences, 17: 698-709.

Cruden, A.M. and Varnes, D.J., 1996. Landslide types and processes. Landslides Investigation and Mitigation Special Report 247, National Academy Press, Washington, DC, USA: 36-75.

Gerraghty, D. and Lewis, M., 1983. Downie Slide Field Report on contract CR-10A Geology and Construction. B.C. Hydro and Power Authority.

Jory, L.T., 1974. Appendix 2 Summary of Geology. Revelstoke Project Downie Slide Investigations Summary of 1973 Exploration Program. BC Hydro Report No. 725: 1-8.

Kalenchuk, K.S, Hutchinson, D.J. & Diederichs, M.S., 2009. Downie Slide - Interpretations of complex slope mechanics in a massive, slow moving, translational landslide. GeoHalifax2009, Canadian Geotechnical Conference, Halifax, Canada: 367-374.

Kalenchuk, K.S., Diederichs, M.S. and Hutchinson, D.J. 2012. Three-dimensional numerical simulations of the Downie Slide to test the influence of shear surface geometry and heterogeneous shear zone stiffness. Computational Geosciences, 16(1): 21-38.

Kalenchuk, K.S., Hutchinson, D.J. and Diederichs, M.S. 2013a. Geomechanical interpretation of Downie Slide considering field data and three-dimensional numerical modelling, Landslides, 10(6): 737-756.

Kalenchuk, K.S., Hutchinson, D.J. and Diederichs, M.S. 2013b. Downie Slide: numerical simulation of groundwater fluctuations influencing the behaviour of a massive landslide, Bulletin of Engineering Geology and the Environment, 72(3-4): 397-412.

Patton, F.D. and Hodge R.A.L., 1975. Airphoto study of the Downie Slide British Columbia. Report prepared for the Downie Slide Review Panal British Columbia Hydro and Power Authority Revelstoke Dam Project: 1-21.

Piteau, D.R, Mylrea, F.H and Blown, I.G., 1978. Chapter 10: Downie Slide, Columbia River, British Columbia, Canada. Rockslides and Avalanches. Elsevier, New York, USA: 365-392.

Wheeler, J.O. 1965. Big Bend map-area, British Columbia (82 M east half). Geological Survey of Canada, Paper 64-32: 1-37.