Downie Slide - Interpretations of complex slope mechanics in a massive, slow moving, translational landslide

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ABSTRACT
Downie Slide is a massive, slow moving, translational landslide located on the west bank of the Revelstoke reservoir in south-eastern British Columbia. Recent site investigation, complemented by a review of historical geological records, reveals heterogeneous geological and geomechanical characteristics and complex hydrological conditions. Using GIS tools, information pertaining to lithology, hydrogeology and geomorphology has been amalgamated with over 30 years of slope monitoring data in order to visualize and analyze site conditions. The sensor web, made up of inclinometers, extensometers, survey monuments and piezometers, has tracked the spatial and temporal variations in the orientation and magnitude of slope deformations as well as fluctuating ground water conditions during implementation of slide drainage and over the development and operating life of the Revelstoke dam. Through analysis of geology, geomorphology and slope monitoring data it is possible to make interpretations of modern slide behaviour; this paper suggests a new hypothesis for the landslide mechanisms at Downie Slide. This detailed study of the Downie Slide has systematically processed geological information and large quantities of slope monitoring data using GIS tools to improve the understanding of mechanisms controlling mass movement in huge, complex, translational landslides.

RÉSUMÉ
Le glissement de terrain translationnel Downie est un bloc massif qui se déplace lentement et se situe sur la rive ouest du réservoir à Revelstoke dans la région sud-ouest de la Colombie Britannique. Un programme de reconnaissance ainsi qu'une revue des données géologiques historiques ont révélé des caractéristiques géologiques hétérogènes et des conditions hydrologiques complexes. En utilisant les outils d'un programme géographique informatique, les données lithologiques, hydrologiques et géomorphologiques ont été amalgamées avec plus de 30 ans de données de surveillance du mouvement de terrain pour visualiser et analyser les conditions du site. Le système de surveillance, qui se comprend d'inclinomètres, extensomètres, monuments d'arpentage, et piézomètres a suivi les variances spatiales et temporelles dans l'orientation et la magnitude des déformations ainsi que les variances en conditions hydrologiques durant l'exécution d'un système de drainage pendant le fonctionnement du barrage Revelstoke. Avec l'analyse des données de la géologie, la géomorphologie et les données provenant du système de surveillance, il est possible d'interpréter les mouvements de l'écroulement modernes. Cet article suggère une nouvelle hypothèse concernant la géotechnique de l'écroulement. Cette étude détaillée a traité les données géologiques et les données de glissements de l'écroulement en utilisant les outils d'un programme géographique informatique pour mieux comprendre les mécanismes contrôlant le mouvement dans les écroulements gigantesques, complexes et translationnels.

1 INTRODUCTION

Downie Slide, according to the Cruden and Varnes (1996) classification scheme, is a massive, active, composite, extremely slowly moving rockslide. It is located approximately 64 km north of Revelstoke, British Columbia, Canada, on the west bank of the Columbia River Valley (Figure 1). The slide was identified in 1956 during reconnaissance mapping of the river valley for a possible dam site. The British Columbia Hydro and Power Authority, recognizing the potential hazard to future hydro-electrical developments, initiated an intensive exploration program to collect geological information and groundwater data, monitor slope movements, and define sub-surface shear zones by drilling and seismic methods (Moore et al. 1997).

Geographic information systems (GIS) have been utilized to amalgamate information pertaining to geology, hyrdrogeology, morphology and over 30 years of slope monitoring data in order to assess the nature of Downie Slide, interpret physical behaviour and analyze geological controls on slope deformations. It has been found that groundwater conditions play an important role in modern slope behaviour as the most significant changes to monitored slope deformations occurred in response to drainage system development (Imrie and Moore 1991, Kalenchuk et al. 2009).

Downie Slide is characterized by numerous morphological features which indicate a long and complex deformation history. The slide has, historically, been interpreted and analysed as a massive translational slide (for example, Enegren and Imrie 1995, Kjelland 2004). This paper suggests a new hypothesis that interprets Downie to be a massive, complex, compound rockslide where the main landslide mass features translational and rotational mechanisms, and secondary slumps and disturbed zones have de-stabilized in response to the main instability. Further investigation and numerical modelling is ongoing to test the geomechanical feasibility of this newly proposed hypothesis.

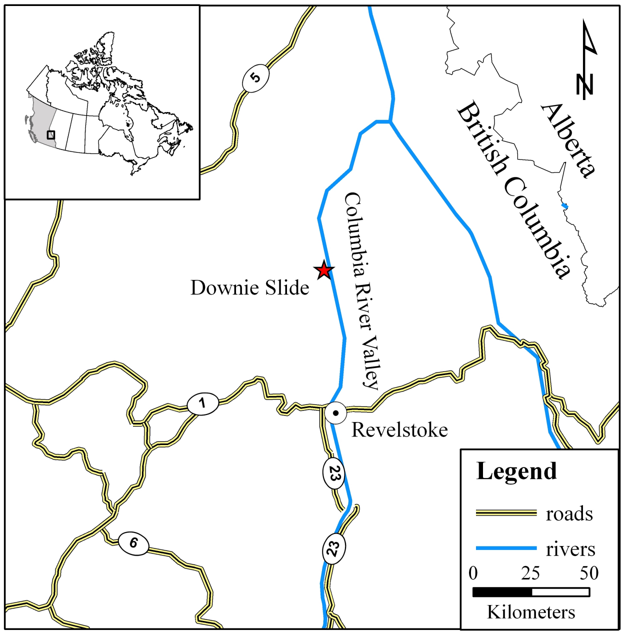

Figure 1. Location map of Downie Slide north of Revelstoke in south-eastern British Columbia

2 SITE DESCRIPTION

2.1 Landslide Geometry and Geology

This 1.5 x 10^9 m3 rockslide measures 3300 m from toe to head scarp, reaches a maximum thickness of 245 m and extends 2400 m along the river valley (Enegren and Imrie 1996). The landslide lies within a thick continuous sequence of pelites, (metamorphosed sedimentary rocks), semipelites and minor psammites (metamorphosed sandstone) (Brown and Psutka 1980, Jory 1974) (Figure 2). A well developed mica foliation dips toward the east, facilitating instability as landslide slip surfaces follow micaceous layers within weak pelitic horizons (Imrie et al. 1991). Multiple slip surfaces (Figure 3) have been interpreted from borehole logs and inclinometer records. A dominant shear zone defines the basal slip surface and two secondary shear zones occur within the landslide mass.

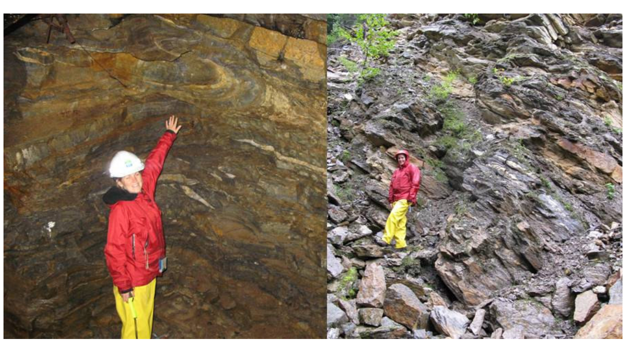

Figure 2. (left) Interlayered gneiss and schist grade rocks are folded and (right) the rockmass within the landslide is highly fractured

2.2 Hydrogeology

Multiple water tables have been identified at Downie (Figure 3). Controlled by the low permeability of the basal and middle slip surfaces, one is below the basal slip surface, one is between the basal and middle slip surfaces and a possible third water table may occur above the middle slip surface. These water tables vary in piezometric head, groundwater chemistry, and their response to seasonal precipitation and changing boundary conditions controlled by reservoir operations.

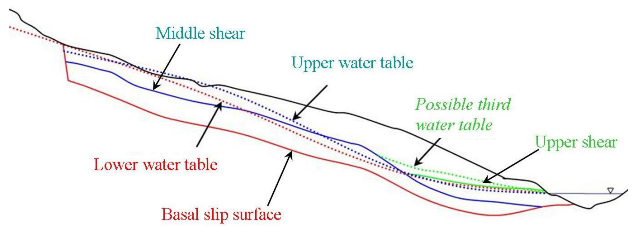

Figure 3. Three shear zones and multiple water tables have been identified within the Downie Slide. The lower water table is confined below the basal slip surface, the middle water table is confined between the basal and middle shear zones and a possible third water table is found above the middle shear zone

The British Columbia Hydro and Power Authority has been monitoring piezometric levels at Downie Slide for over 30 years. This monitoring records water table fluctuations in response to changing groundwater boundary conditions controlled by the development of drainage infrastructure, reservoir filling and gradual losses of drainage capacity (Kalenchuk et al. 2009). Prior to reservoir filling a drainage system was developed as a remediation measure aiming to more than offset the water table rise that was anticipated with inundation of the landslide toe. Development of drainage infrastructure occurred in stages between 1974 and 1982 comprising of two adits totalling 2.43 km and more than 13.6 km of boreholes. Reservoir filling began in October, 1983 and was completed by August, 1984. Over the operating life of the reservoir the drainage system has been slowly deteriorating due to borehole shearing and infilling by silty material and bio-accumulation.

GIS software has been used to visualize and compare groundwater levels over specific periods of time in order to assess the influence of changing boundary conditions. Figure 4 illustrates the middle water table response to these changing conditions; the lower water table shows similar trends. With the development of drainage infrastructure groundwater levels were significantly lowered in areas close to adits and boreholes, while portions of the slope more distal to drainage infrastructure saw no significant changes (Figure 4, top). Groundwater response to reservoir filling was observed only by piezometers proximal to the inundated landslide toe (Figure 4, middle). Increases in groundwater levels have been observed over the reservoir operating life with gradual losses in drainage system capacity (Figure 4, bottom).

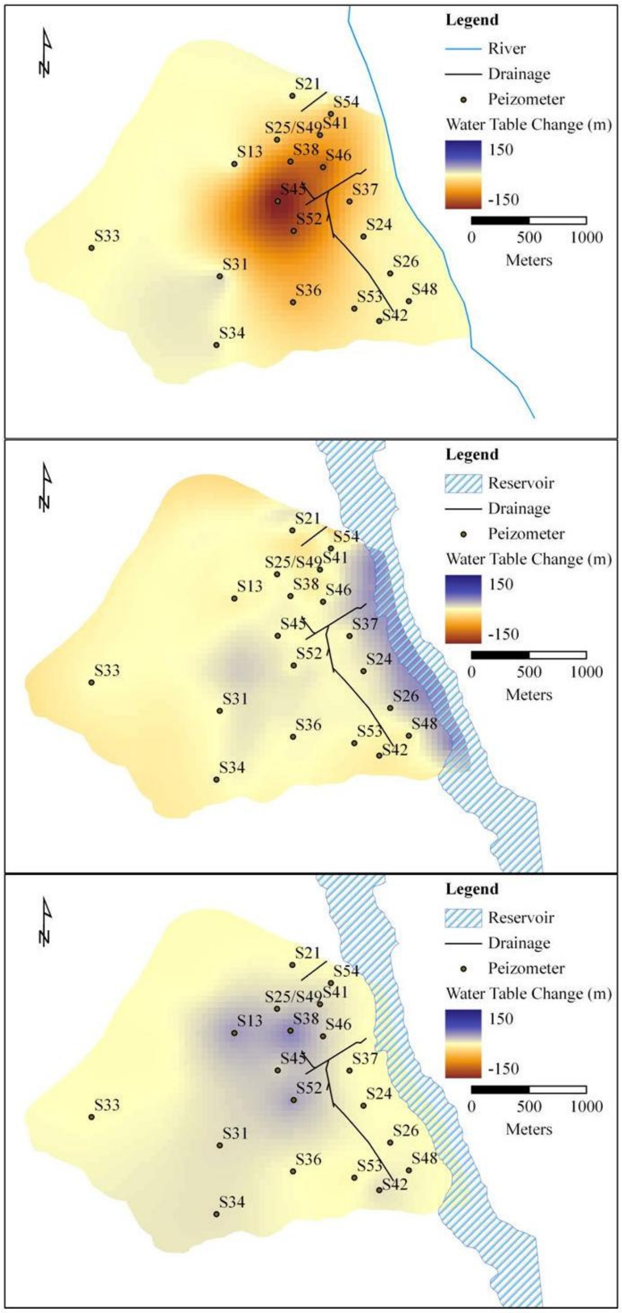

Figure 4. Fluctuations in groundwater levels in the middle water table at Downie Slide in response to changing boundary conditions: (top) drainage development, (middle) reservoir filling, (bottom) gradual losses of drainage capacity (modified from Kalenchuk et al. 2009)

Seasonal groundwater fluctuations show peak levels occurring annually between June and August. Using GIS the spatial variance in magnitude of seasonal fluctuations can be visualized (Figure 5). The magnitude of seasonal fluctuations is greatest in areas closest to recharge zones in the upper portions of the landslide near the head scarp (near piezometers S33 and S34).

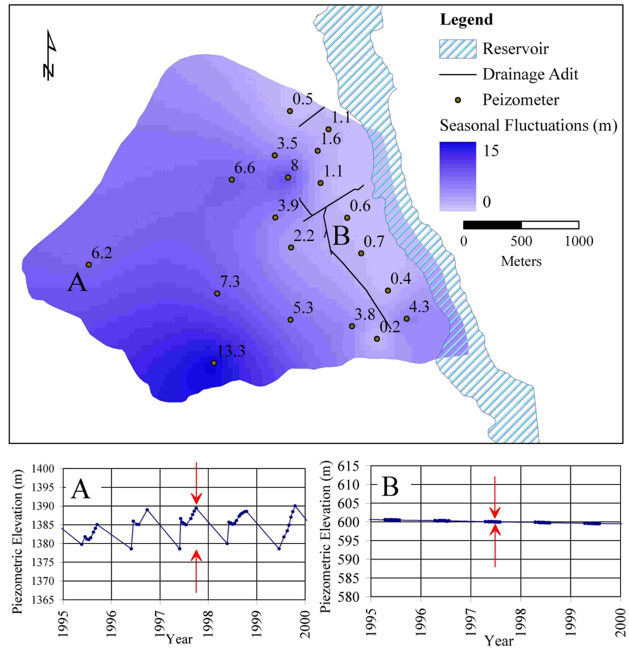

Figure 5. Spatial variance in the magnitude of seasonal groundwater fluctuations at Downie Slide. Data from point A (piezometer S33) shows high seasonal fluctuations near the headscarp recharge zone, and data from point B (piezometer S37) shows very little annual variance

2.3 Geomorphology

Several types of landforms defining the Downie Slide morphology suggest a complex landslide evolution. The slide mass is divided into a number of zones including: the upper region, the talus slopes, the central region, the lower region, the active zone within the lower region, the north knob, the toe slump, the destabilized north zone, and the lobe (Figure 6). Each zone shows distinct morphological features and variable slope behaviour and failure mechanisms as discussed in the subsequent section.

The landslide is bounded by a main head scarp to the west, a side scarp to the south, and a less obvious boundary to the north (Figure 6). The scarps are the most visually dominant morphological features of Downie Slide. These sub-vertical scarps exceed, in places, 125 m (Brown and Psutka 1980). The blockiness of the scarp face and the overall geometry are controlled by three joint sets (two sub-vertical and one sub-horizontal) (Figure 7). The north landslide boundary is more difficult to define. In aerial photographs the north scarp can be seen at high elevations as a lineament (solid line shown in Figure 6), and at lower elevations the boundary is less pronounced (dashed line in Figure 6).

Below the head scarp, the upper region is characterized by hummocky terrain where large rock blocks are separated by tension cracks, internal scarps and jumbled talus. The partially disturbed rock blocks and extensional features give the impression of some retrogressive behaviour. The upper portion of the slope gradually extends down slope, as the middle and lower portions of the slide fail slowly into the valley. These observations are in agreement with Patton and Hodge (1975) and Piteau et al. (1978). Patton and Hodge (1975) noted that the large rockmasses separated by prominent linear depressions may represent later collapses of a predecessor of the present headscarp.

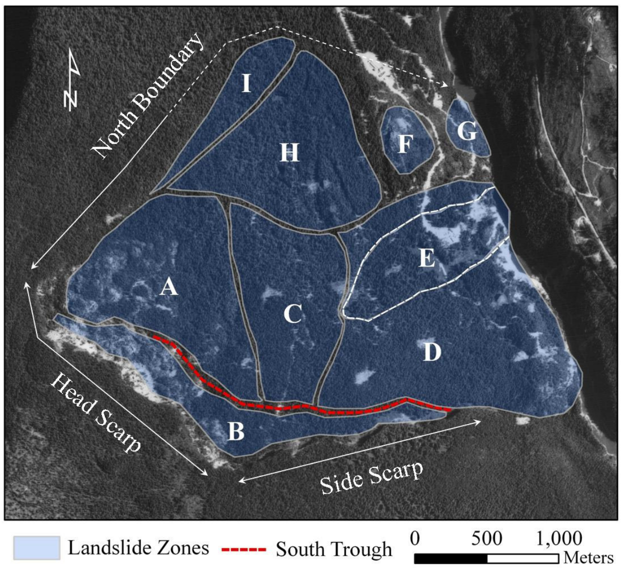

Figure 6. Morphological zones of Downie Slide: (A) upper region, (B) talus slopes, (C) central region, (D) lower region, (E) active zone within the lower region, (F) north knob, (G) toe slump, (H) destabilized north zone and (I) lobe

A distinct depression, the south trough shown in Figures 6 and 8, runs parallel to the southern slide boundary. Within this trough, tension cracks and small scarps are observed. Talus, shed from the head and side scarps, flows into the trough. This depression possibly marks the southern edge of the main landslide mass. Patton and Hodge (1975) made similar interpretations and concluded that the width of this trough, measured in the direction of movement, provides a rough estimate of total displacement (250 to 300 meters). The talus slopes at the base of the scarps are evidence of a long, continuous history of scarp-sloughing as some boulder fields are overgrown by moss and old-growth forest, while other areas are fresh.

The central region of Downie Slide features mature growth forest on gentle slopes with few disrupted outcrops, depressions or crevices (Patton and Hodge 1975, Piteau et al. 1978). Down slope, the lower region is characterized by more irregular topography with numerous depressions, crevices, fracture traces, and internal scarps (Patton and Hodge 1975). The southern portion of zone D is a broad, over-steepened ridge, at the base of which is active colluvial accumulations. Along the toe a bench, or step, is formed by slump blocks. The active zone, making up the northern portion of the lower zone, is a depressional basin defined at the edges by scarp features.

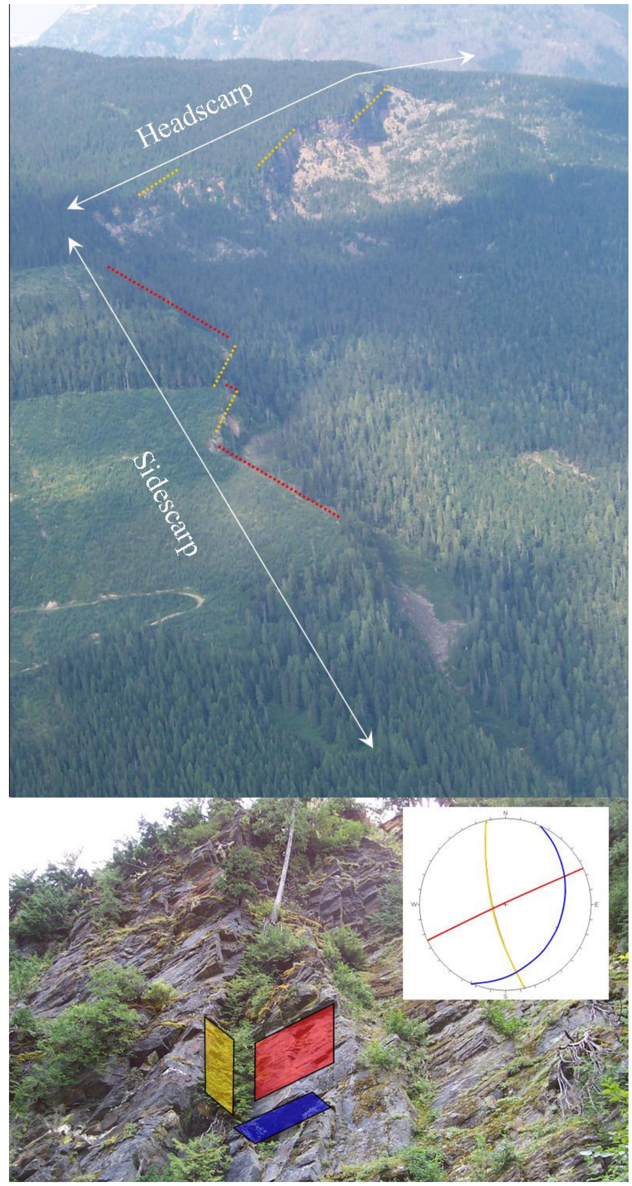

Figure 7. The blockiness and geometry of the Downie head and side scarps are controlled by jointing (top) view of the scarps looking west, (lower) blocky nature of the scarp face, (inset) stereonet illustration of joint sets identified at Downie

A prominent outcrop, termed the north knob, dominates the lower north-east portion of the slide (Figures 6 and 9). The outcrop is surrounded by extensional features created by material failing away from this zone in all directions (Figure 10). Immediately to the east of the north knob is a talus slope (Figure 9). Lacking a source zone, this bulging, over-steepened talus slope appears to be translating outward from the landslide. Down slope from here is an active toe failure (shaded area in Figure 9) bounded by the distinct scarp features illustrated in Figure 11. Between the talus slope and the active north toe are linear depressions orientated parallel to the reservoir.

Figure 8. The south trough, (top) internal scarp feature at the edge of the depression, (bottom) overgrown jumbled talus shed from scarp

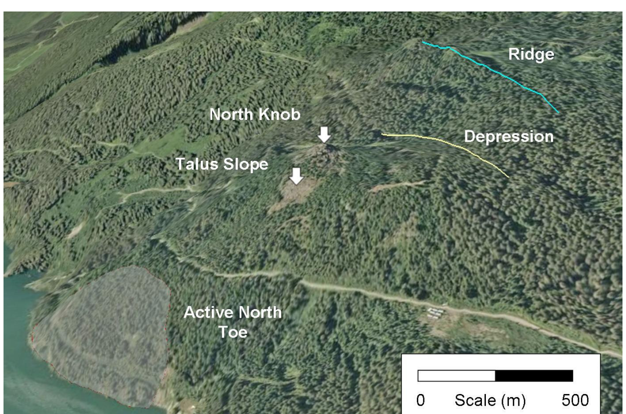

Figure 9. View, looking southwest, of the north knob area, illustrating the talus slope and active north toe (shaded area) located down slope from the knob and the prominent depression and ridge features (marked in yellow and green) immediately up slope (base image taken from Google Earth version 5.0)

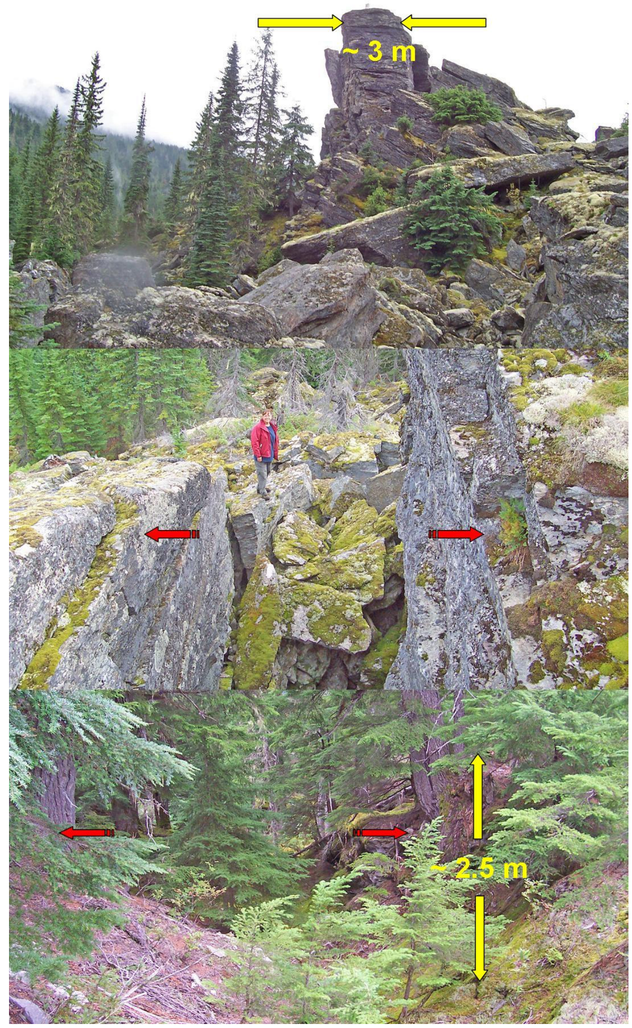

Figure 10. (upper) North knob as viewed from the north, (middle) tension crack found southeast of the knob, and (lower) extensional feature observed in the depression located west of the knob (red arrows indicate direction of extension)

Figure 11. Active north toe area; (left) scarp exposure, (right) offset at the side boundary of the active area (blue lines indicate magnitude of offset, yellow arrow shows direction of motion)

3 LANDSLIDE BEHAVIOUR

3.1 Historical

Slope deformations were likely initiated after the last glacial period (9,000 to 10,000 years ago) and prior to the eruption of Mount Mazama (6,600 years ago). This time frame is supported by evidence summarized by Piteau et al. (1978) including: the distribution of till found in the central area of the slide, large blocks in the upper portions which would have been carried away during glaciation, and the occurrence of Mount Mazama ash within a large alluvial fan on east side of valley which must have developed post-slide as it has not been destroyed by rubble. Recent initiation is ruled out by the lack of slide-destroyed vegetation.

It is hypothesized that movement may have begun during glacial regression (Piteau et al. 1978, Brown and Psutka 1980, Kjelland 2004). The over-steepened south portion of the lower region and the north knob may suggest that glacial ice provided some restraint; otherwise these rockmasses would have translated rather than bulged (Piteau et al. 1978). Also, no scarps exist below about 625 m elevation; this may indicate that a scarp could not develop where ice was still present (Piteau et al. 1978). The hypothesis of ice restrained movement is supported by lack of debris on the opposite river bank and the absence of a slide-induced lake (Piteau et al. 1978). Following the assumption that the slide was activated following the last glacial period, instability may have been initiated as glacial ice receded from the valley (Kjelland 2004), and erosion by the Columbia River, removed support form the toe of the slope. At this time, groundwater pressures would have been high due to melting ice contributing to instability of the slope in early postglacial times (Kjelland 2004).

The total slide displacements are estimated to be between 250 and 300 m and a 10º counter-clockwise rotation of joint structure has been observed in aerial photographs and field mapping (Patton and Hodge 1975, Piteau et al. 1978). The initial velocity of the slide is unknown and it is believed that no movement has been rapid (Imrie et al. 1991, Brown and Psutka 1980). The Columbia River has been gradually deflected eastward by slide displacement; this is evident in the river gravels of a buried river channel found in two drill holes near the toe of the slide (Brown and Psutka 1980).

3.2 Modern

Sensor webs, made up of inclinometers, survey monuments and piezometers, are used to track the orientation and magnitude of deformations as well as conditioning factors such as water table fluctuations. Over 30 years of field data from sensor webs have been amalgamated in GIS and subsequently visualized, interpreted and analyzed. Today Downie Slide is active and is, according to the Cruden and Varnes (1996) classification scheme, extremely slow moving with a few localized “active” zones which are very slow moving. Behaviour of the landslide varies spatially and temporally. Different regions of the slope deform at different rates and these rates vary over time with changing boundary conditions.

Analysis of slope monitoring data concludes that landslide hydrogeology is an important boundary condition influencing the modern behaviour of this massive landslide. Figure 12 illustrates the change in deformation rates, measured by survey monuments, in response to drainage development and reservoir filling, as well as over the operating life of the hydroelectric facility. It is important to note that accelerations and decelerations less than ± 5 mm/year and annual displacement rates less than 5 mm/year indicate effectively no change in deformation, as such small deformations fall within the error margin of the measured data.

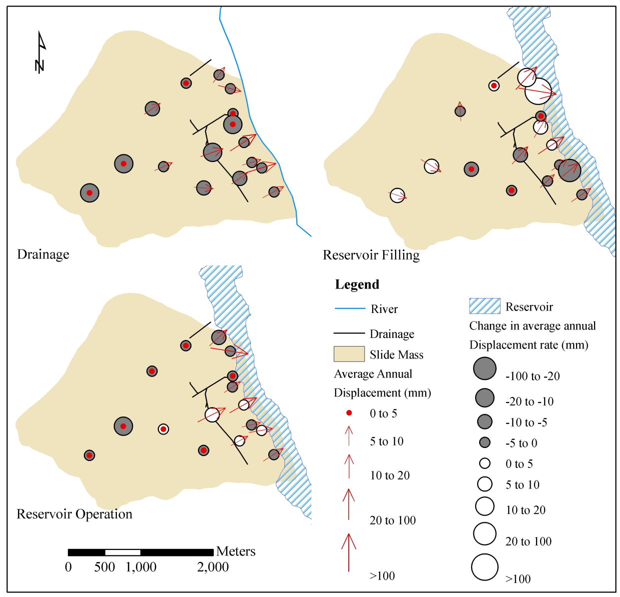

Figure 12. Deformation rates vary spatially and temporally, as different zones of the landslide show variable response to changing groundwater boundary conditions

With the development of drainage infrastructure decelerations were observed by all survey monuments. Then, with reservoir filling, the central and lower regions of the slide continued to decelerate, with the exception of some acceleration in the active zone. Considerable accelerations were observed in the toe slump zone. Small accelerations were also observed in the upper region, however these are not believed to be directly related to reservoir filling, as groundwater levels in the upper slope were not influenced by toe inundation (Figure 4). Since reservoir filling, the slide mass has maintained fairly constant deformation rates. The toe slump zone, while still showing considerable displacement rates, has decelerated slightly since initial inundation. Accelerations and decelerations measured in the upper region most likely reflect movements of individual large rockmass and localized scarp sloughage.

4 INTERPRETATIONS OF LANDSLIDE MECHANICS

Traditionally the Downie Slide has been interpreted as a massive translational slope failure (for example, Piteau et al. 1978, Patton and Hodge 1975, Enegren and Imrie 1995). This interpretation is supported by the landslide shear surface following weak mica foliation, where most of the landslide mass is moving extremely slowly down slope with anomalous behaviour observed near the toe reflecting localized failure mechanisms. Following this interpretation Patton and Hodge (1975) and Piteau et al. (1978) provided explanations for many of the morphological features.

It is generally agreed that the hummocky terrain of the upper region is made up of large rockmasses separated by extensional features; this zone may represent retrogressive behaviour that may or may not have involved the later collapses of a predecessor to the present headscarp. Piteau et al. (1978) suggested that based on the dimensions of the scarps and the topography the initial direction of movement would have been to the northeast, rather than towards the river. They pointed out that this would explain the diffuse nature of the north boundary and the “bunching” of material near the north knob (Piteau et al. 1978).

Patton and Hodge (1975) suggest that the numerous enclosed depressions, found predominantly in the lower region, may be voids which develop by a number of mechanisms, such as: when the moderately stiff mass slides over underlying depressions, there is a change in slope of the basal sliding surface, differential movements occur, or ice blocks covered by slide debris melt. Depressions found upslope from the north knob may have similar origins, or are more easily accounted for as tensile zones related to the slide passing over a bedrock escarpment located along the sliding surface (Patton and Hodge 1975).

4.1 A New Hypothesis

One of the most puzzling features at Downie Slide is the north knob. This pinnacle of rock is a topographic high point on the slide, and interestingly the survey instrument located on top of this pinnacle shows no cumulative displacements over time. It is apparent from tension cracks and the observation of toppling failure that material fails away from this topographic high in all directions. Material lost to the north, east and south is shed down slope towards the river valley. On the west side of the north knob material fails away from the river valley. Therefore on the “up-slope” side of the north knob there should, in theory, be some material accumulation, however, in reality, this is the location of a linear depression (Figure 9). As such, we must ask the question: where has this material been transported to if the knob itself is not moving down slope? Patton and Hodge (1975) proposed that the depression is most easily explained by the slide passing over a bedrock escarpment located along the sliding surface. If this were the case however, it would be expected that the north knob would also, to some degree, be translating down slope. The northeast directed slide movement proposed by Piteau et al. (1978) is a plausible explanation for the scarp geometry and poorly defined north boundary, however, this explanation does not work well to explain observations of 10º counter-clockwise rotation of the joint structure or the apparent loss of material from the west side of the north knob.

A new hypothesis of the Downie Slide is proposed to explain the nature of the puzzling north knob, and all other morphological zones. The south portion of the slope including the upper, central and lower regions is interpreted to make up the main landslide mass (Figure 13). The south boundary of the main slide is then defined by the south trough. The talus slopes between the south trough and the scarps are the result of gradual raveling of the exposed sub-vertical faces. The north disturbed zone and the lobe are interpreted as subsequent secondary failures that would have initiated in response to the main instability to their south, with northeast directed movement in the lobe, and south-southeast directed movement in the disturbed north zone. The depression just west of the north knob can then be explained as material translated towards the main landslide mass as the south edge of the north disturbed zone is dragged down slope. The north knob is a stable region, with some localized failure along the reservoir in the active toe slump zone.

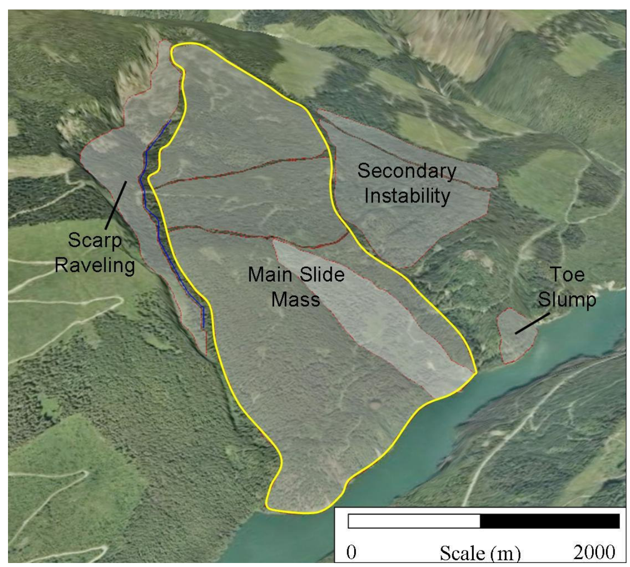

Figure 13. Illustration of the proposed movement boundaries (looking northwest), red lines define the morphological zones (refer to Figure 6), yellow line defines the main landslide mass (base image taken from Google Earth version 5.0)

This hypothesis is supported by spatial variance in the landslide deformations. The toe slump region is a small localized slide which exhibits a different failure mechanism than the main landslide mass and responds differently to changing groundwater boundary conditions. For instance the considerable accelerations in response to the reservoir filling and ongoing displacement rates are an order of magnitude higher than the main landslide body. The toe slump may have been triggered by gradual slope over-steepening in response to glacial and fluvial erosion, the larger instability of the main landslide mass to the south, or both.

Deformations within the main slide mass are discriminated between the upper, middle and lower zones. Movement mechanisms in the upper region, by this hypothesis, are similar to earlier interpretations (Patton and Hodge 1975, Piteau et al. 1978, where the hummocky terrain is thought to have developed in extension by differential movement of large rock blocks. The upper and middle region of the slide are translational where the shear surface follows weak micaceous foliation planes. The lower region, in particular the active zone, is the most active area of the main landslide body. This lower region has a rotational component where the shear surface deviates from the foliation plane as it bends to daylight in the river valley. This proposed hypothesis does account for the rotations observed in the joint structure within the slide mass.

5 SUMMARY

Since Downie Slide was first recognized in 1956 during reconnaissance mapping for a possible dam site, the slope has been studied extensively (for example, Patton and Hodge 1975, Piteau et al. 1978, Brown and Psutka 1980, Imrie et al. 1991, Enegren and Imrie 1995, Moore et al. 1997, Kjelland 2004). The geological setting is well understood, long term groundwater monitoring provides an impressive basis for hydrogeology analysis and detailed interpretations of slide morphology have been done. GIS amalgamation of geological, hyrogeological, and morphological information, with slope monitoring data, has made it possible to visualize modern slope behaviour and interpret the slide mechanisms. Modern deformations are largely controlled by groundwater boundary conditions, and significant slope deceleration occurred in response to drainage development. Accelerations at the toe slump during reservoir filling did not impose any significant broader scale slope response, and deformation rates recorded during the reservoir operating life have remained more or less constant.

Historically, Downie Slide has been interpreted as a massive translational slope failure. However, more complex mechanisms must be taken into account in order to explain the various morphological observations. The new hypothesis proposes that Downie Slide is a complex, compound landslide, where the main slide mass has triggered instability to the north and the scarps have gradually raveling well past the main slide boundary, developing significant talus slopes. Ongoing research uses three-dimensional numerical models to simulate various hypotheses of landslide geometry to explore if interpretations such as the one suggested here are geomechanically reasonable.

ACKNOWLEDGEMENTS

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