28 Downie Slide, British Columbia, Canada

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This chapter is dedicated to John Francis Psutka (1953–2011), whose work contributed greatly to it. He was an accomplished engineering geologist who loved to work on Downie and many other mountain slopes bordering hydroelectric reservoirs in British Columbia.

ABSTRACT

The Downie Slide case history demonstrates the importance of detailed site investigation and long-term monitoring, as well as the need for reinterpretation of the local geologic, structural, and groundwater conditions, and reassessment of slope stability as new information becomes available. Forty-five years of investigation, monitoring, and assessment have been carried out at Downie Slide. The long history of studies, coupled with recent technological advances in analytical tools, has enabled us to better understand the behavior of large complex landslides.

28.1 INTRODUCTION

Downie Slide, the largest known active slope instability in the world, is located 64 km north of the Revelstoke Dam on the west bank of the Revelstoke Reservoir, in the Columbia River valley, British Columbia, Canada (Fig. 28.1). This massive, active, composite, extremely slow-moving rockslide has a volume of 1.5 billion m³. It measures 3300 m from toe to head scarp and 2400 m along the toe, with a maximum thickness of approximately 250 m. Downie Slide is thought to have been initiated by glacial retreat, approximately 10,000–12,000 years ago (Piteau *et al.*, 1978; Brown and Psutka, 1980). Total slope displacements are estimated between 250 and 300 m (Patton and Hodge, 1975), but there is no evidence that the slide failed rapidly or blocked the valley (BC Hydro, 2010).

Downie Slide was first identified in the 1950s during reconnaissance mapping for potential dam sites on the Columbia River (Blown, 1966). Interest in this massive slope instability grew through the 1960s, when the potential hazard that a landslide of this magnitude poses to hydroelectric operations was recognized. This chapter focuses on the site investigations, landslide stability analyses, and hazard mitigation that were initiated prior to the reservoir filling (1984/5) and that are still ongoing today.

28.2 SITE INVESTIGATION

Several holes were drilled near river level during early mapping in the 1950s (Blown, 1966). CASECO Consultants Ltd., designers of the Mica Dam, which is located 70 km upstream from Downie Slide, initiated an extensive exploration program in 1965, when the potential for Downie Slide material to block the valley and therefore flood the toe of the Mica Dam was being investigated. This program involved drilling five exploration boreholes totaling about 1000 m in length. Three holes were drilled on the landslide to obtain groundwater profiles and to install inclinometers, and two non-instrumented exploration holes were drilled on the opposite side of the valley.

Site investigation of the landslide continued through the 1970s and 1980s by BC Hydro, under the guidance of the Downie Slide Review Panel. The panel of experts also oversaw design and construction of an extensive drainage system. By 1985, reservoir filling was completed and the involvement of the review panel was reduced to a review of annual reports.

With each drilling program, complementary investigations and studies were also carried out, including:

- *surface surveys* (geological mapping, aerial photography studies, surface displacement surveys, meteorological observations, and stream monitoring)
- subsurface investigations (seismic refraction surveys, inclinometer, extensometer, and piezometer installations, downhole geophysics, groundwater monitoring, and permeability testing)

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Fig. 28.1. Left: Overview photo of Downie Slide viewed from the east side of the valley, August, 2008. Right: Location of Downie Slide, north of the town of Revelstoke, British Columbia, Canada.

- *material property evaluation* (mineralogy and material strength laboratory testing of gouge and rock samples, and petrographic studies)
- modeling, including scaled physical model and mathematical studies of slide-generated waves, groundwater modeling, and slope stability studies.

Seismic monitoring was attempted, but was unsuccessful because ground movements could not be differentiated from surface disturbances such as tree movements in the wind.

Over the operating life of the Revelstoke Reservoir, site investigation has continued during annual site inspections and periodic reviews of monitoring data. Most recently, in 2009, a new geological and geomorphological assessment was conducted, involving surficial mapping, an aerial LIDAR (light, distance, and ranging) survey, and high-resolution aerial photography.

28.3 HAZARD MANAGEMENT AND MITIGATION

Two hydroelectric projects, Mica and Revelstoke dams, operate upstream and downstream, respectively, from Downie Slide. Although the likelihood of rapid failure of Downie Slide is now considered to be low, the possibility still remains. One consequence of a rapid slide failure is the potential formation of a slide-generated wave that could impact Revelstoke Dam. Another consequence of rapid slide failure is blockage of the valley with a landslide dam and subsequent uncontrolled rise of the reservoir level upstream that could impact the toe of Mica Dam. Furthermore, the eventual failure of a landslide dam could cause a downstream surge of water and debris toward Revelstoke Dam.

The magnitude of kinetic energy associated with slow-moving, massive landslides makes it impossible to completely stop their movement. Therefore, approaches to hazard mitigation of such landslides should aim to improve stability by reducing and controlling movement rates. Monitoring should be implemented to track changes in the slope behavior. Emergency warning and response plans should be developed, for situations when the acceptable displacement rate is exceeded, which are commensurate with the potential consequences of failure.

Groundwater pressures, geomechanical properties, geologic setting, and topography are all significant contributors to the ongoing instability of Downie Slide. For such a large landslide, the only factor that can be controlled is the groundwater pressure, and therefore drainage was the only means available to reduce slope movement rates. BC Hydro committed to develop a drainage system that more than offset the decrease in stability caused by submergence of the toe, and to install a comprehensive monitoring system to evaluate the effects of remedial measures. An extensive underground drainage system was constructed between 1974 and 1982. Two adits totaling more than 2.43 km and in excess of 13.6 km of drainholes were installed. The adits are primarily located within the landslide mass itself, and the drainholes extend into the rock mass above and below the basal shear zone. As required by the BC Comptroller of Water Rights, the reservoir was raised in stages as the performance of the slide and drainage works was monitored. In 1984, the expert review panel to the Comptroller concluded that "the effects of the reservoir at the slide were of small scale" and that "the drainage monitoring and surveillance system had functioned as planned" (BC Hydro, 1987). Groundwater pressures slowly rose in the slide in the 1990s, thus additional drainholes were installed in 2007/8 to ensure compliance with the recommendation that "annual peak water levels do not exceed the values assumed for stability calculations" (BC Hydro, 1987).

28.4 SITE CHARACTERIZATION

Regional and local geological and morphological information has been collected from borehole geology logs, geological mapping of the drainage adits, geological and geomorphological mapping of surficial conditions, aerial photograph interpretation, and analysis of LIDAR data. This information has been documented in reports by numerous authors (Wheeler, 1965; Jory, 1974; BC Hydro, 1974, 1976, 1978, 1983; Brown and Psutka, 1980; Bourne and Imrie, 1981; Kalenchuk *et al.*, 2012a).

28.4.1 GEOLOGIC SETTING

In the Columbia River valley area, a metasedimentary sequence consisting primarily of thinly bedded quartzites, semipelites, psammites, calc-silicates, and marbles (Brown and Psutka, 1980) overlies the Monashee Complex, a high-grade metamorphic core complex (Read and Brown, 1981; Scammell and Brown, 1990, and references therein; Armstrong *et al.*, 1991; Johnston *et al.*, 2000). The east-dipping Columbia River Fault Zone truncates the metasedimentary sequence on the east bank of the Columbia River valley across from the toe of Downie Slide, and a foliated biotite granodiorite pluton occupies the hanging wall (Brown and Psutka, 1980). Cataclastic fabrics across the Columbia River Fault Zone are evident in a zone up to 1 km thick, and more recent brittle faulting has resulted in localized zones of clay and graphitic gouge (Brown and Psutka, 1980).

Downie Slide occurs within a thick continuous sequence of pelites, semipelites, and minor psammites. Subtle variation in the rock type and complex interlayering of the schist, gneiss, and quartzite make it impossible to correlate lithological units between boreholes (Jory, 1974; BC Hydro, 1978). Quaternary sediments on the floor and slopes of the valley adjacent to the landslide include local alluvial and colluvial deposits, till, and glaciofluvial sediments (Fulton and Achard, 1985).

28.4.2 STRUCTURAL SETTING

The Downie Slide region has experienced three phases of deformation. Phase 1 deformation is defined by isoclinal folding with the same geometry as Phase 2 and, as such, exerts the same influence on the landslide. The location and attitude of the second and third phases of deformation and their associated fabrics control the slide geometry (Brown and Psutka, 1980). The axial surfaces of Phase 2 folds are parallel to the primary compositional layering (Brown and Psutka, 1980). Phase 2 deformation has produced a penetrative axial planar mica foliation which dips 20° eastward; the basal shear zone of the landslide has developed parallel to this foliation. Phase 3 deformation is defined by open, upright folds with moderate to steeply west-dipping axial surfaces (Brown and Psutka, 1980). Phase 3 deformation is prominent west of Downie Slide, but dies out to the east and has only minor significance at the site of the landslide. Its steep north-south-trending axial planes,

however, may have produced release surfaces for the formation of the head scarp.

The rock mass is highly fractured, and three joint sets have been identified (Imrie *et al.*, 1992). Joint set 1 (J1) is parallel to foliation; two sub-vertical sets dip roughly east (J2) and north (J3). J1 joints are continuous, closely spaced, smooth, and wavy or planar. They may have micaceous gouge coatings and/or surface staining, and offset J2 and J3. J2 joints are closely to moderately spaced and are characterized as smooth and wavy to planar with surface staining, chloritization, and clay infilling. J3 joints are closely to moderately spaced and are characterized as planar and smooth to wavy and rough. All joint sets are well developed in the gneiss units. In the weaker, more ductile schist, J1 and J2 joints are poorly developed or widely spaced, and J3 joints are absent (BC Hydro, 1983).

28.4.3 GROUNDWATER

Multiple water tables are controlled by the low permeability of the shear zones at Downie Slide. A lower water table is confined below the basal slip surface; an upper water table is confined within the slide; and a perched water table may occur near the landslide toe (Kalenchuk *et al.*, 2009a). The welldefined, confined lower and upper water tables can be differentiated from each other by piezometric head, geochemistry of the groundwater (Bourne and Imrie, 1981), and the magnitude of the response to changing groundwater boundary conditions and seasonal fluctuations. The water table positions, shown in Figure 28.2, are drawn down within the lower half of the slope by the drainage works (see Section 28.6.2).

Groundwater levels peak seasonally between May and August, first at lower elevations and later in the year within the higher regions of the slope. Water levels decline through the fall, and minimum levels are reached during the winter months. The magnitude of seasonal fluctuations differs spatially (Fig. 28.3). Typical water table fluctuations on the upper part of the landslide are of the order of 10 m, but they locally exceed 25 m and, in rare instances, can be up to 85 m. These high-amplitude seasonal variations are controlled by infiltration in the highly fractured and dilated upper region of the landslide, which is a recharge zone. No streams cross this area. Through the central portion of the slope, 5-m fluctuations are normal, and near the toe, seasonal variations are nearer 1 m. Streams are observed through these regions, where infiltration is limited by thick ground cover. The small magnitude of seasonal fluctuations near the reservoir reflects relatively steady-state reservoir levels and the influence of drainage measures.

28.4.4 SHEAR ZONES

Shear zones at Downie Slide include a well-developed basal slip surface and secondary shears. The basal shear zone is associated with weak mica-rich horizons parallel to the foliation. Near the toe of the landslide, this shear zone curves upward and cross-cuts the foliation to outcrop near the





bottom of the river valley. This prominent shear is characterized by closely to very closely spaced, foliation-parallel joints, with areas of fractured and crushed material, clay and mica gouge, and chlorite-altered clay (BC Hydro, 1978, 1983; Bourne and Imrie, 1981).

The basal shear zone at Downie Slide ranges in thickness from less than 2 m to nearly 50 m (Fig. 28.4). The shear zone is typically thinner where slip surfaces follow foliation planes, and thicker where the shear cross-cuts foliation; these differences contribute to spatial variation in the magnitude of deformation observed across Downie Slide. Numerical modeling by Kalenchuk *et al.* (2012b) assumes that thin regions are effectively stiffer than thicker regions. Differences in shear zone stiffness induce localized stress concentrations, which contribute to complex three-dimensional slope deformation.

28.4.5 LANDSLIDE GEOMETRY

The irregular nature of displacements in large slow-moving landslides is an indication of complex landslide geometries.

The three-dimensional extent of the landslide mass is defined by the geometry of the basal slip surface. The true geometries of slip surfaces within massive landslides are largely unknown and must be interpolated from the available data obtained from surface and subsurface site investigation programs. The threedimensional geometry of the Downie basal slip surface has been interpreted from shear zone intercepts in borehole geology logs, inclinometer profiles, and the landslide boundary on the surface identified from aerial photographs and LIDAR data (Kalenchuk *et al.*, 2009b).

Figure 28.5 illustrates two different interpretations of the Downie Slide basal slip surface geometry. The first interpretation is an oversimplified bowl-shaped geometry. The second interpretation is a moderately undulating geometry, interpreted using a stepped minimum curvature algorithm. This undulating geometry is geologically reasonable for Downie Slide because the shears are associated with foliation, which has been gently warped by folding. The stepped feature along the south and west margins of the landslide matches the prominent side and head scarps, although it should be noted that the true depth of



Fig. 28.3. Spatial variation in the magnitude of seasonal groundwater fluctuations in the upper water table at Downie Slide. Data from point A show high seasonal fluctuations near the head scarp recharge zone; and data from point B show very little annual variation (from Kalenchuk *et al.*, 2009a). The lower water table shows similar trends.



Fig. 28.4. Variability in the thickness of the Downie Slide basal shear zone.

the sub-vertical face extending below the topographic surface is unknown.

Three-dimensional interpretations of shear surface geometry are important for landslide studies. Knowledge of shear surface locations across the entire slope provides improved estimates of landslide volume, which could only otherwise be resolved from estimates of surface area and thickness. Furthermore, three-dimensional geometries are required for state-of-the-art numerical stability analyses. Figure 28.5 illustrates normalized contour plots of surficial deformation magnitudes. The undulating, geologically realistic, three-dimensional geometry is better able to reproduce observed slope deformation patterns than the oversimplified bowl-shaped geometry.

28.4.6 LANDSLIDE MORPHOLOGY

Kalenchuk *et al.* (2012a) have classified the modern Downie Slide as a composite rockslide, meaning that different styles of movement are observed across different areas of the displaced mass. They identified a number of zones based on morphological features identified from airborne LIDAR data, observations made during site visits, and analysis of spatially discriminated failure mechanisms and deformation patterns. The main slide body is divided into the Upper, Central, and Lower regions (Fig. 28.6). Secondary instabilities include the South Trough, Talus Slopes, Oversteepened Slopes, Toe Slump, Basin, Lobe, and Disturbed North regions. The North Knob is an inactive area. This landslide zonation is based on observations of the modern Downie Slide; the mechanisms of failure during initial instability may have differed significantly from those observed today.

- Upper Slope: This zone is characterized by hummocky terrain comprising large, partially disturbed rock blocks, separated by extensional features that are littered with jumbled talus.
- South Trough: The South Trough extends approximately parallel to the side and head scarps and contains numerous internal scarps and tension cracks. This depression has been interpreted to mark the southern boundary of the main landslide mass (Patton and Hodge, 1975; Kalenchuk *et al.*, 2009a). Patton and Hodge (1975) concluded that the total slide displacements are about 250–300 m based on the position of the South Trough.





Fig. 28.5. (a) Illustration of the three-dimensional numerical model used to simulate slope behavior. (b) Three-dimensional interpretations of shear surface geometry. (c) Comparison of deformations measured in numerical models to field observations of landslide behavior. Contour plots show deformations standardized by plotting displacement rate contour intervals corresponding to the average and standard deviation of each dataset.



- **Talus Slopes**: This zone comprises talus derived from gradual raveling of the scarps. Raveling has been occurring for a long time, as is shown by the presence of both newly deposited debris and talus covered with mature coniferous forest.
- Central Slope: This zone features gentle slopes overgrown by mature forest. The South Central area is relatively featureless, suggesting that this portion of the slope has remained intact or that there has been little deformation since initial landslide activation. A subtle topographic break marks the boundary between the North and South Central regions, suggesting greater activity to the north, where the terrain is slightly hummocky.
- Lower Slope: This zone features irregular terrain marked by depressions, crevices, internal scarps, and fractures. The southern part of the Lower Slope is a broad, oversteepened ridge. East-west-trending lineaments indicate north-south extension through the southern part of the Lower Slope; however, without detailed mapping, it is difficult to conclude whether the movement is by pure extension or by translational extension, with some component of downslope shearing. Downslope deformation is, however, indicated by the slight clockwise rotation in lineament orientation at lower elevations and bulging of the toe. The northern portion of the Lower region is the Active Zone – a basin marked by hummocky disturbed terrain and by scarps at its edges.
- North Knob: This feature is a prominent topographic high, marked by talus-covered slopes and surrounded on all sides by extensional features. Data from a survey monument on the peak of this feature indicate that it has been stationary throughout the period of monitoring.
- **Oversteepened Slopes:** This zone is located east and north of the North Knob. Curved tree trunks and fresh surface colluvium suggest that this area is actively deforming, although there is no evidence of modern, deep-seated displacements.
- Toe Slump: An active area bounded by scarp features occurs near the landslide toe just north of the North Lower region.
- **Basin**: The Basin is an area bounded to the west, north, and east by extensional features including scarps and sinkholes. It slopes gently to the south, draining into the North Lower region. This area is not monitored, thus there are no data to define the magnitude and direction of modern, local deformation. However, material from the Basin may have gradually moved south-southeast toward the Active Zone.
- **Disturbed North Region**: This is a region of secondary failures, hypothesized to have initiated in response to the main instability to the south.
- Lobe: The Lobe is also interpreted to be a secondary failure. Its upper portion is not morphologically suggestive of landslide activity. The lower portion is terraced, giving the impression of shallow failure in glacial deposits or colluvium, rather than deep-seated failure in bedrock. Northeast-directed surficial movement in this zone is indicated by curved tree trunks.

Downie Slide is bounded to the south and southwest, respectively, by prominent side and head scarps (Fig. 28.7). These scarps are near-vertical and reach heights up to approximately 120 m. The west limit of the head scarp coincides with the hinge zone of a major monoclinal flexural fold associated with Phase 3 deformation (Brown and Psutka, 1980). The north landslide boundary, which can be clearly recognized in LIDAR imagery (Fig. 28.6), has a distinct northeast-trending linear alignment. Where this boundary curves to the southeast near the toe of the landslide, streams continue to flow northeast toward the river valley. This linearity suggests a structural control on the location of the north landslide boundary.

28.5 MONITORING

Groundwater and displacement monitoring was initiated at Downie Slide in 1965, prior to construction of the drainage system in order to provide baseline data to evaluate the effectiveness of the drainage. Intense monitoring was carried out during reservoir filling and for about a year after the reservoir reached full capacity. During the period of toe inundation, an automatic data acquisition system (ADAS) and an automatic early-warning system were deployed to provide immediate notification of any sudden changes in slide behavior. Currently there are nearly 200 instruments monitoring Downie Slide, 65 of which are automated, including piezometers, inclinometers, extensometers, GPS survey monuments, water volume flumes in the adits, and tunnel convergence pins.

Recently, more accurate and reliable sensors, dataloggers, and freewave radio data transmission have been added to the monitoring system. Enhanced real-time monitoring has been achieved with both in-house custom and commercial software. The automated instruments installed at Downie Slide are typically automatically read and stored every 6 minutes. When an instrument has neared or exceeded the threshold level, an e-mail and phone message are automatically sent to the surveillance engineer and on-call person in the BC Hydro Surveillance Department.

28.5.1 DISPLACEMENT MONITORING

Slope movements are the most important indicator of the stability of Downie Slide, and changes in deformation rates are indicative of the effectiveness of the drainage system and the effects of toe inundation by the reservoir. Once reservoir filling was complete, slope movement trends – and therefore warning bounds – became known, and monitoring frequency was reduced. The displacement monitoring network has been periodically expanded and upgraded, and currently consists of 17 inclinometers, 25 surface monuments, and 4 extensometer nests.

SURFACE MONUMENTS

Surface monuments have been surveyed since 1975. The initial surveys were triangulation-trilateration surveys that required up to 7 days of field measurements and several days of data processing. In 1998, the survey was converted to a GPS network; it now





Fig. 28.7. Left: View of the Downie Slide scarps, looking west. Right: The prominent head scarp reaches heights of up to 120 m.

takes 1 day to acquire the data and about a day to process the data and complete the survey. Of the 25 surface monuments currently monitored, 16 are located on the landslide, 6 are on the perimeter, and 3 are control points on the east bank of the Columbia River. The perimeter survey points are monitored to provide an alert of displacements that could indicate enlargement of the current slide mass; these show little displacement, as would be expected.

INCLINOMETERS

Full-length inclinometer profiles are measured once each year. If unusual readings are detected in the hole, a second set of readings is taken to verify the change in movement rate. Monitoring data are routinely reviewed to determine whether new zones of movement have developed, or to check previously defined movement zones for any changes in the thickness of the shear zone. Seven of the inclinometer holes contain multiple inplace probes that are linked to the ADAS system. These probes monitor movement rates at discrete zones throughout the slide, including the basal slip surface and internal shears, and also measure surface and near-surface displacements.

When monitoring slopes, it is important to recognize that there are inherent instrumentation errors that need to be corrected. Interpretation of inclinometer data must consider sensitivity to instrument drift, spiraled inclinometer casings, and sensor alignment. These corrections can be applied to known data errors, such as zero-shift errors and rotational errors. However, inclinometer data, particularly in deep holes, are best used to describe the nature of deformation through the hole and to provide a sense of where localized deformation is occurring rather than to develop an exact displacement profile (Mikkelsen, 1996).

28.5.2 WEIR MONITORING

Water flow from drain holes has been measured in the past, but these measurements are highly variable and are difficult to automate. Weir monitoring was initiated in 1975 in Adit 1, and in 1978 in Adit 2. In 2007, a second weir was installed in the south branch of Adit 1 so that the flows from the north and south extensions of the drainage adit could be monitored individually. Flow from the adits, as recorded in hourly readings, is highly affected by seasonal variations in the groundwater regime. The highest flow rates generally occur in late May, following a doubling of drainage water volume during the month. Through the summer and fall months, the water levels fluctuate and then drop back to their lowest levels in the winter. A significant decrease in the flow rate out of the adits could be a sign of diminishing drainage system effectiveness.

28.5.3 PIEZOMETER MONITORING

Currently there are about 100 operational piezometers monitoring groundwater conditions at Downie Slide. The ADAS system is used to collect data from 28 key piezometers within the slide area on a 6-hour interval throughout the year. Manual measurements of the non-automated piezometers onsite are taken several times during the spring, summer, and fall seasons.

28.5.4 LIDAR

Airborne LIDAR was flown over Downie Slide in 2009. The resulting "bare earth" image of the ground surface of Downie Slide proved to be an invaluable resource (Fig. 28.6). In the future, repeated LIDAR surveys will be used to evaluate differential

movements, assuming that sufficient slide movement occurs to distinguish these changes from noise or inaccuracy of the data.

28.5.5 INSPECTIONS

The Downie Slide monitoring program also includes inspections of the slide surface and the drainage system. The site is inspected at least monthly between April and October by technical staff, and annually by a rockslide specialist. Winter conditions impede physical access to the site. Site activities include routine maintenance of the adit ventilation and lighting, site access roads, adit generator, fans and lighting, and the permanent site vehicle, and also repair and replacement of instrumentation sheds, vegetation clearing from helicopter landing pads and survey monuments, and maintenance and calibration of ADAS instrumentation.

28.6 SLOPE BEHAVIOR

The pattern of current deformation at Downie Slide is complex, as the magnitude of deformation varies both spatially and temporally. Spatial variations in surficial deformation patterns of landslides can be influenced by the three-dimensional shape of the failure surface, different thicknesses of the moving mass, heterogeneous material properties, and differences in the state of stress associated with the geologic history, groundwater conditions, and previous movement. Temporal variations are influenced by changing boundary conditions, for example groundwater fluctuations or changing material properties due to deformation or weathering processes.

28.6.1 SPATIAL VARIATION IN MODERN SLOPE BEHAVIOR

Downie Slide does not behave as a monolithic instability; instead, different zones deform differently (Kalenchuk *et al.*, 2012a). In the following discussion, Cruden and Varnes' (1996) description of landslide deformation rates is used: rates less than 16 mm per year are extremely slow, and rates between 16 mm per year and 1.6 m per year are very slow.

The morphological zones described previously (Fig. 28.6) display the following deformation patterns.

- The Upper Slope shows evidence of retrogressive failure and has the highest movement rates (about 30 mm per year). Large blocks are interpreted to have broken off the scarp progressively, thereby increasing the spatial extent of the landslide over time.
- Translational sliding occurs over the Central Slope, but displacements are extremely slow (less than 5 mm per year). Inclinometer data from the northern part of the Central Slope indicates that the deformation is dominantly surficial, with minor slip on the basal slip surface and minor internal strain through the landslide profile. There is, however, evidence in the inclinometer records of deeper-seated creep below the basal slip surface. Close- to moderate-spaced jointing below



Fig. 28.8. Annual displacements defined by deformation measured since impoundment of the Revelstoke Reservoir (data from 1985–2003).

the landslide basal slip surface is documented in borehole geology logs.

- The Lower Slope exhibits translational and rotational sliding. The active landslide zone is found within the North Lower Slope, and the Lower Slope features extensive toe sloughing along the reservoir shoreline. Deformation rates are extremely slow to very slow through the Lower Slope, in the order of 5–10 mm per year on the main slide mass and 20 mm per year in the Active Zone.
- Active deformation in the Disturbed North Region is probably surficial; however, there are no subsurface deformation data and there is no monitoring in this portion of the slope to quantify rates.
- The Lobe is a secondary failure and is active today. However, there is no monitoring on this portion of the slope; thus movement rates are unknown.
- The North Knob is inactive and makes no contribution to modern landslide behavior.
- Although material from the Basin has gradually moved toward the active area, there are no survey monuments to provide rates or directions.
- The Oversteepened Slopes show surficial deformation of about 20 mm per year since reservoir filling.
- The Toe Slump is a localized instability with anomalously high deformation rates in excess of 200 mm per year since reservoir filling that are not representative of the overall slide behavior.

Figures 28.5 and 28.8 illustrate spatial variation in the behavior of Downie Slide. With the exception of surficial instabilities near the reservoir, the highest deformation rates are on the upper part of the slope; the central region of landslide has the lowest rates; and moderate rates are observed near the toe.

28.6.2 TEMPORAL INFLUENCE OF GROUNDWATER LEVELS ON SLOPE DEFORMATIONS

Groundwater levels have a strong influence on the behavior of Downie Slide (Fig. 28.9), and have changed in response to





implementation of drainage works and reservoir operations. Dewatering resulted in a significant drawdown of the water table throughout the central portion of the slope. During reservoir filling, the landslide toe was inundated by about 70 m of

water. Over the operating life of the reservoir, the effectiveness of the drainage system has decreased, perhaps due to a variety of factors: bacterial sludge accumulation, calcification, gas bubbles evolving from the groundwater, migration of fines into The slope response to changing groundwater boundary conditions differs spatially (Kalenchuk, 2010). A marked reduction in slope movements through the central and lower portions of the landslide was achieved by construction of the drainage system. The most significant change is in the lower region of the slide. Instruments tracking surficial instabilities near the landslide toe show little change because the water table is now located below these shallow failures. Changes in rates observed on the upper slope are considered to be a function of localized behavior of large blocks attributed to scarp retrogression.

No changes in movement rates were detected during reservoir filling. The changes in the Lower Slope region were negligible, and the Central Slope region even experienced minor deceleration, although this change is not interpreted to be a response to reservoir filling, given its distance from the landslide toe. Surficial movements, particularly in the Oversteepened Slopes and the Toe Slump, accelerated following inundation. This change is a localized response to the rise in groundwater levels at the landslide toe. The Upper Slope of the landslide shows a minor acceleration following inundation, which we again interpret to be localized.

No significant change in landslide behavior has been observed at Downie Slide since reservoir filling, and the landslide, as a whole, is considered to be in steady state condition (Kalenchuk, 2010). Temporal variations in movement continue to be observed on the Upper Slope, which is most influenced by infiltration. These variations may be related to precipitation and snowmelt, but meteorological data are not available to test this possibility. Minor accelerations, likely a response to a small rise in groundwater levels, have been observed in the Active Zone (North Lower region). The overall rate of movement of the landslide is too small to raise concerns about overall slide stability.

28.6.3 IMPLICATIONS OF SLOPE STUDIES FOR LANDSLIDE HAZARD MANAGEMENT

Interpretation of the differing deformation patterns of a large landslide requires an understanding of how failure mechanisms differ between specific areas of the slope. At Downie Slide, deformation rates are anomalously high in the Toe Slump and Oversteepened Slopes, where surficial failure mechanisms are operating. Recognition of these secondary instabilities has significant implications for the interpretation of monitoring data for slope hazard management. If the secondary surficial deformation rates were misinterpreted as being representative of global behavior, the entire landslide would be perceived to be moving much more rapidly than it is. Furthermore, these secondary instabilities have been shown to be susceptible to changing boundary conditions that do not influence the entire landslide mass. Thus localized surficial accelerations are not necessarily a cause for alarm.

As information continues to become available at Downie Slide, consideration should be given to the spatial distribution of monitoring instruments. The retrogressive Upper Slope region exhibits some of the fastest movement on the landslide, yet characterization of this part of the slope is currently based on a single data point (M19). It is possible that movement rates at this single point may be anomalously low or high. Future additions to the instrumentation network at Downie Slide should take into consideration sparsely monitored slope regions, particularly those interpreted to be contributing to the overall landslide behavior. Areas that contribute less to the overall behavior of the landslide, for example the Lobe, might be given a lower priority for increased instrumentation.

28.7 STABILITY ASSESSMENTS

Detailed site investigations have provided the information necessary to analyze slope stability. A number of stability assessments have been completed for Downie Slide, including two-dimensional numerical modeling of the slope by Enegren (1995) and Kjelland (2004). More recently, Kalenchuk (2010) and Kalenchuk *et al.* (2012a, 2012b) have completed a rigorous analysis using three-dimensional numerical modeling that took into account complex three-dimensional shear surface geometry, interactions between discrete landslide zones, heterogeneity of material properties, and multiple water tables. This modeling has improved our understanding of massive landslide geomechanics.

Numerical simulation of changing groundwater conditions yielded reasonable correlations with field observations (Fig. 28.10). Specifically it simulated:

- · the slowing of the landslide following drainage works
- accelerations of the lower portion of the slope after reservoir filling
- the negligible effect of the gradual loss in the performance of the drainage system over the operating life of the reservoir, with the exception of minor accelerations near the toe
- the different responses of the morphological regions to changing groundwater levels.

The development of calibrated numerical models capable of reproducing field observations enables experts to examine potential trigger scenarios and the effectiveness of engineered mitigation approaches. Forecasting has been completed for Downie Slide using three-dimensional, hybrid continuum– discontinuum numerical models (Fig. 28.11). The results suggest that overall simulated slope behavior would change little in response to rapid reservoir drawdown. It is likely, however, that surficial instabilities at the landslide toe would increase in such a scenario. Total loss in drainage capacity would likely result in accelerations in movement of the same magnitude, but in the







Fig. 28.11. Sophisticated numerical models have been used to forward test potential trigger scenarios at Downie Slide; hypothesized deformation rate change in response to (top) rapid reservoir drawdown, and (bottom) total loss of drainage capacity (after Kalenchuk, 2010).

opposite direction, as those observed during the original installation of the drainage system. Although total failure of the drainage system is extremely unlikely, particularly with continued site maintenance, simulations indicate that this worst-case scenario would only cause minor slope accelerations, at a maximum at the low end of the range of very slow slides.

28.8 CONTINUED WORK ON HAZARD ANALYSIS AND RISK MANAGEMENT

Regular and appropriate maintenance and inspection protocols have been developed over the 35 years that BC Hydro has monitored Downie Slide. With this experience, BC Hydro has added suitable instrumentation types to extend the spatial coverage of deformation monitoring.

The monitoring and assessment program was established before the construction of Revelstoke Dam, with the objective of determining whether the drainage measures would increase slope stability enough to more than offset any decrease in stability caused by submergence of the toe of the slide, as specified in the original conditional water license issued by the BC Comptroller of Water Rights.

Further investigation and analysis of data gathered from the landslide indicate that the potential for rapid catastrophic failure

is even lower than originally thought. The overall rates of movement fall into the very slow to extremely slow categories, and the landslide can be divided into a number of different regions that display varying mechanisms of instability. Approximately one-fourth of the landslide mass lies on a horizontal slide surface near the toe, thereby providing considerable resistance to sliding (BC Hydro, 2010). Should any appreciable increase in rate occur in the future, a substantial lead time is anticipated to respond to and understand the change. Ongoing maintenance of the equipment and upgrades of the monitoring system will be required to retain this capability. In addition, monitoring of adit drainage flows and drainage system inspections must continue, in order to ensure that drainage efficiency is maintained.

To comply with the original requirements of the water permit, BC Hydro has been working to maintain the 10 percent increase in stability generated by implementation of the drainage works. The recent work to add more drainage capacity to the system in 2007 and 2008 was a response to the reduction in stability to an estimated 8 percent above the original conditions. However, given the very low probability of failure of a large volume of the slide mass, a partial lessening of these stringent conditions seems warranted before investment is made in more drainage works.

28.9 SUMMARY

Downie Slide has been intensely studied for 45 years. Work on the landslide has provided an evolving and impressive knowledge base of massive landslide geomechanics. Recent improvements in understanding the geomechanics of Downie Slide have significant implications for the continued interpretation of monitoring data and for hazard management. Defining a "significant" change in landslide behavior is only meaningful when the overall behavior of the slope can be modeled and understood.

Recognition of primary and secondary instabilities is important to the analysis of deformation data for slope hazard management. Surficial secondary instabilities near the toe of Downie Slide have higher deformation rates than those throughout the main body of the landslide. If these secondary deformation rates were misinterpreted as being representative of the overall behavior, the entire landslide would be perceived to be moving much more rapidly than it is. In addition, secondary instabilities are susceptible to changing groundwater conditions that do not influence the behavior of the entire landslide mass.

This case history provides an excellent example of the use of advanced numerical models in tandem with high-quality instrumental data. Once models simulating observed behavior have been calibrated effectively, they can be used to examine the possible influence of a variety of potential destabilizing or conditioning factors in order to evaluate the risk of lower-probability events that have not yet been experienced at the location of the landslide. Finally, this case history provides an excellent example of the use of drainage as a means of stabilizing large, slow-moving rockslides.

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