Displacement Behaviour of the Checkerboard Creek Rock Slope

THOMAS W.G. STEWART AND DENNIS P. MOORE

ABSTRACT

A slowly displacing rock slope, involving approximately 3 million m^3, located 1.5 km upstream of the Revelstoke Dam, in the Selkirk Mountains of British Columbia, has been the focus of a detailed investigation and slope monitoring program. The investigation and assessment have focused on the potential for a rapid slope failure that could cause a landslide-generated wave in the reservoir. Monitoring results indicate a seasonal pattern to the slow displacement process, beginning in the autumn when conditions are generally wetter, and continuing through the winter snowfall and snowmelt. During late spring and summer, very little displacement occurs. The monitored displacement behaviour provides some insight into the understanding of slowly deforming slopes, frequently described in the literature as mountain slope "creep" or "mass rock creep." Detailed numerical modelling studies have been carried out to investigate the current slope displacement behaviour, and have been used to estimate the impact of possible loading conditions, including the potential for rapid slope failure. A key factor in the assessment and prediction of slope behaviour is related to potential strength reduction in the rock mass due to weathering, ongoing slope displacement, or seismic loading. Strength reduction in the rock mass could potentially lead to the formation of a low-strength zone along which a rapid sliding failure could occur. Evolution towards this condition would be revealed by the instrumentation system, justifying the importance of continued slope monitoring. To fulfill this requirement, an Automated Data Acquisition System has been installed to provide real-time monitoring of slope conditions, and alarms have been installed to detect anomalous behaviour. However, this system is less likely to provide sufficient warning of a seismically triggered slope failure that could develop rapidly following a large earthquake.

INTRODUCTION

Slow displacements and a collection of slope deformation features outline a potential bedrock slide on the eastern slopes of the Columbia River valley, approximately 1.5 km upstream of the Revelstoke Dam (Figures 1 and 2). The potential slide has been referred to as the "Checkerboard Creek" rock slope, in reference to the drainage that runs along the eastern and southern sides of the potential slide area.

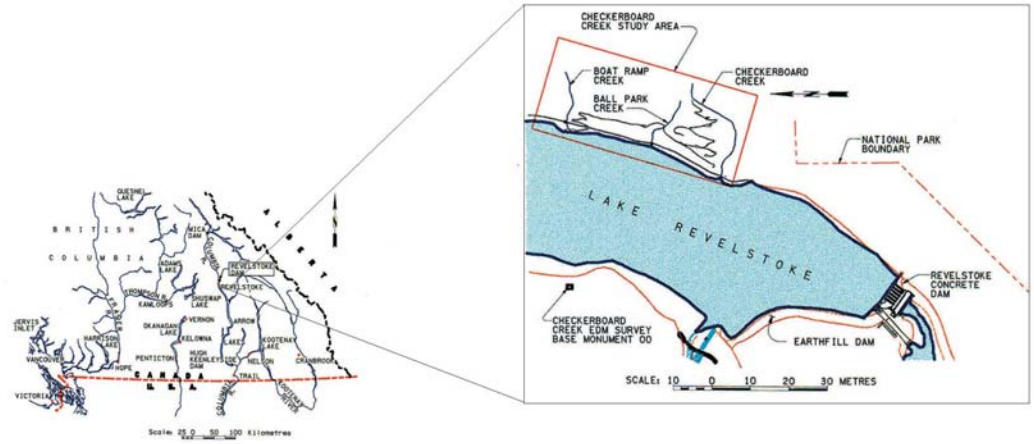


FIGURE 1 *Location plan.*

FIGURE 2 *Oblique view of slope. Checkerboard Creek enters reservoir at right of main rock cut in centre of photo. Main slope area is to left of creek. Note Revelstoke Dam (earthfill section) in foreground.*

Slope investigations were initiated in 1984 following the discovery of a network of apparently fresh tension cracks. The cracks are immediately uphill from a 70 m high excavation required for the relocation of a highway above the future level of Revelstoke Reservoir. The cracks were observed during reservoir slope inspections conducted in association with impoundment of the Revelstoke Reservoir. The initial surface monitoring network has been periodically upgraded and expanded in conjunction with ongoing investigations and inspections. Most recently, an Automated Data Acquisition System (ADAS) providing real-time monitoring has been installed. This paper presents an interpretation of the monitoring results and a discussion of the slope displacement behaviour to date.

SLOPE GEOLOGY

Bedrock is comprised primarily of massive to slightly foliated granodiorite and granite belonging to a tectonic slice of the Selkirk Allochthon referred to as the Clachnacudainn Salient. These rocks overlie the easterly dipping Columbia River fault, which has developed a broad, regional zone of altered and mechanically deformed rock (Lane 1984) that becomes progressively more pronounced with depth below the slope surface. The primary fault zones and related fabric dip easterly into the slope (Figure 3) and, based on slope displacement assessment and analyses, play an indirect role in the kinematics of the displacement process. Piezometric monitoring shows that the eastwardly dipping structures related to the Columbia River fault zone are low-permeability barriers to groundwater flow. They are considered to be barriers to infiltration, and to cause temporary perched groundwater conditions in the upper section of the rock mass where the slope displacement process is currently active.

Rock mass structure in the main slope area is dominated by two well-developed joint sets and the shear/fault zones previously described. The orthogonal joints dip steeply (> 80°), with the primary set generally parallel to the slope contours, and the secondary set striking perpendicular to the slope. The primary joint set exerts structural control on the tension crack development.

Rock mass quality is highly variable, ranging from very strong, fresh, undisturbed and blocky rock, to highly weathered and altered, weak and disturbed rock, containing frequent sheared and crushed zones. Typically, the poor-quality rock is localized within 60 m of the slope surface, where active displacements have been monitored. The underlying rock is generally fair to good in quality, with localized zones of poor rock along shear zones.

GEOMORPHOLOGY

Conspicuous slope features include a series of open tension cracks and partially infilled bedrock linears oriented sub-parallel to the topographic contours. The open tension cracks are exposed in the central slope area between 650 and 740 m elevation (Figure 4) and are seen as discrete, planar to sinuous bedrock cracks in outcrop, and as collapse features where the cracks are covered by thin surficial deposits. The bedrock walls of the open tension cracks show no signs of glacial erosion, which distinguishes them from the infilled linears and indicates that opening of the tension cracks is post-glacial.

Infilled linears on the slope appear as wide (up to 15 m) gullies, benches, and subtle uphill-facing scarps. These features were partially obscured by logging activities during the 1950s. Trenching of these features indicates that bedrock has been glacially scoured along zones of weakness, including faults, shears, and fracture zones, with subsequent infilling by glacial and colluvial deposits. Post-glacial offset in the overburden deposits of up to 25 cm has been observed. Linears with a similar morphology to those at Checkerboard are found throughout this reach of the Columbia River valley and British Columbia, and in many other mountainous regions of the world (Stewart 1997). Numerous studies (Tabor 1971; Radbruch-Hall et al. 1977; Bovis and Stewart

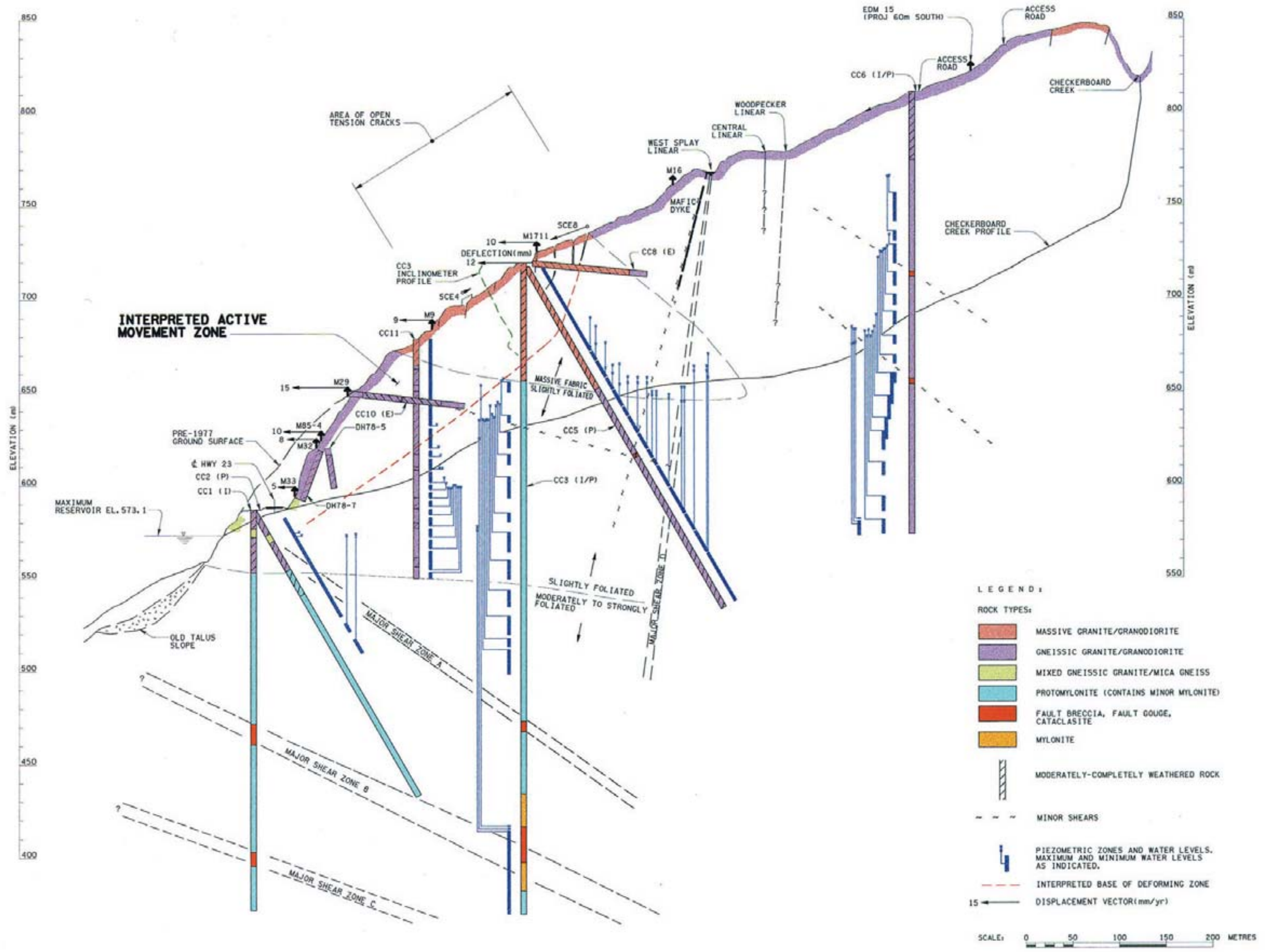


FIGURE 3 *Slope cross-section showing geology, groundwater, instrumentation, and displacement zone.*

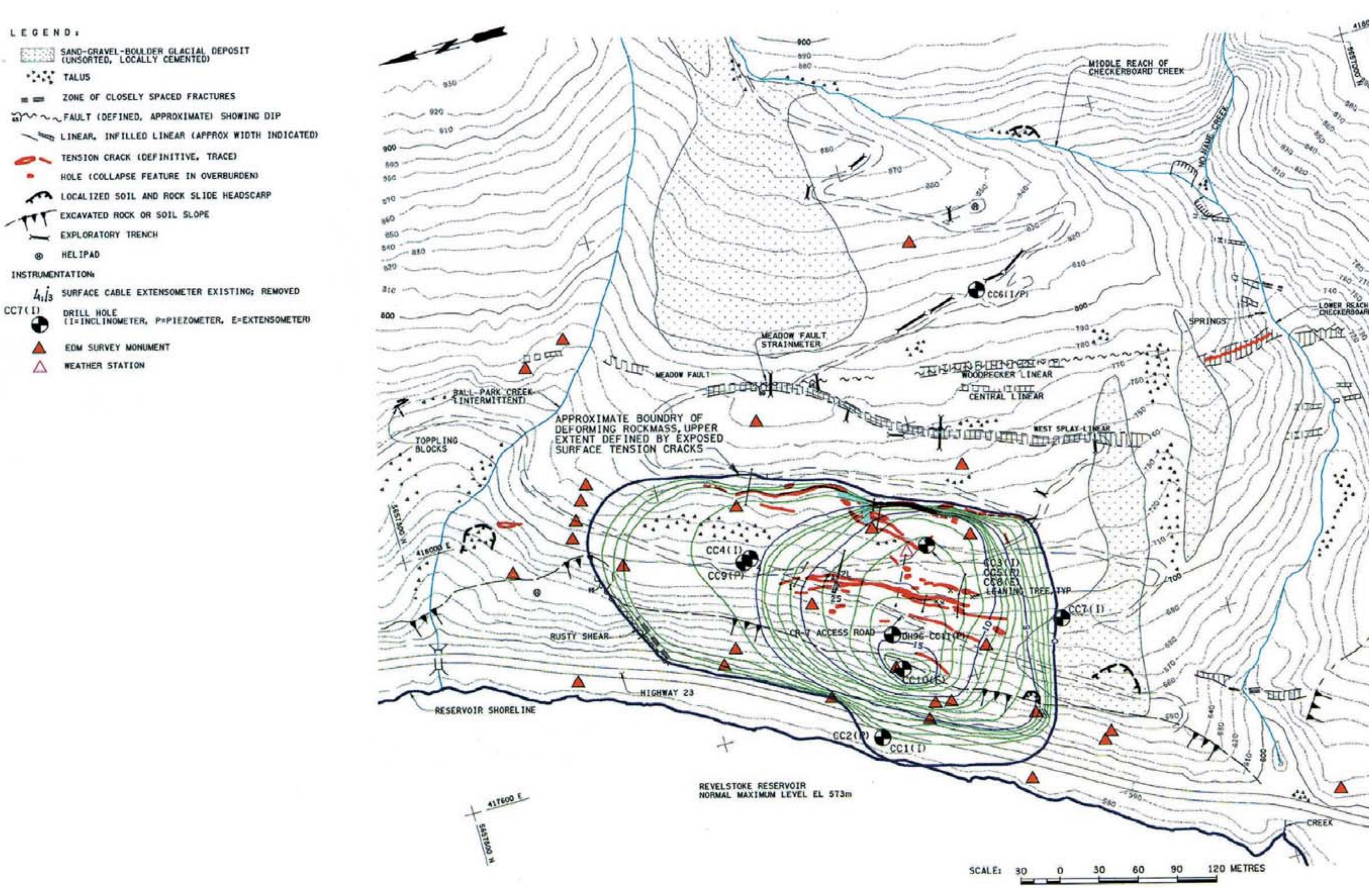


FIGURE 4 *Plan of slope, illustrating slope displacement features, instrumentation, and displacement rate contours.*

1998) have suggested a slope deformation origin for these features; however, evidence at Checkerboard Creek suggests an origin related to both erosional and gravitational effects.

Another significant geomorphic feature is the locally steeper topography in the central area of the slope below the current reservoir level (573 m elevation). This local steepening could have been caused by fluvial erosion of the Columbia River, which flowed along an easterly meander below the central portion of the slope. Alluvial fans limited this erosion at the north and south ends of the main slope area. This active fluvial undercutting could have contributed to the slope displacement process.

SLOPE INSTRUMENTATION

The slope is monitored by an array of instruments installed between 1984 and 2000, including: electronic distance measurement (EDM) surveys, borehole and surface cable extensometers, inclinometers, time domain reflectometry (TDR) cables, a three-dimensional strain gauge, piezometers (standpipe and Multiport types), a weather station, and ADAS equipment (Figure 4).

This instrumentation network has been established to develop a comprehensive understanding of the slope displacement behaviour and the hazard associated with potential slope failure; and to provide an early warning system for detecting potential evolution of the slow displacement process into a rapid failure.

Instrumentation results have indicated a complex slope behaviour pattern, requiring several years to manifest, due principally to the very slow displacement rates of 5–15 mm/yr. The slope conditions and displacement behaviour, discussed in the following sections, are an assessment of present-day behaviour, and should be considered in perspective with the interpreted long history of displacement at Checkerboard Creek.

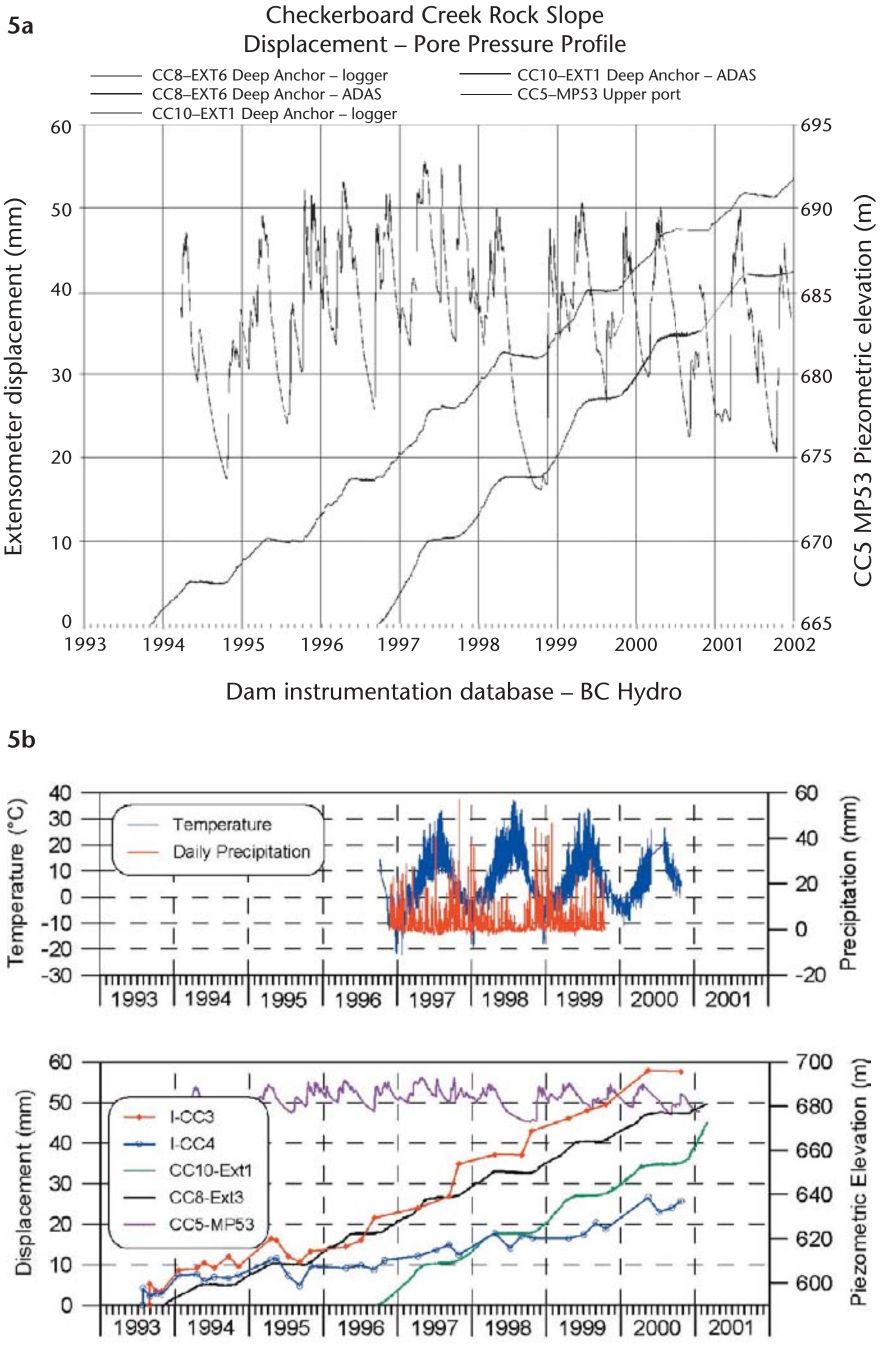
CLIMATIC CONDITIONS

Air temperatures range from –25° to 35°C, with freezing conditions typically prevailing from late November through March. Annual cumulative precipitation is typically 1500–2000 mm, with about 40% falling during October–January, related to regional Pacific storm systems.

GROUNDWATER CONDITIONS

Slope groundwater conditions are based on the results of piezometric profiling during drilling, piezometric monitoring, and general observations during slope mapping and inspections.

Piezometric profiling and piezometer records reveal numerous, discrete pore pressure differences of ≤ 40 m across short lengths of the drillholes (Figure 3). This indicates a compartmentalized groundwater regime in the slope, related to the low-permeability shear zones.



Dam instrumentation database – BC Hydro

FIGURE 5 *(a) Plot of slope displacement and piezometric pressure for the period 1993–2002. (b) Plot of slope displacement, piezometric pressure, and precipitation, illustrating the relationship between piezometric fluctuations and slope displacement.*

Piezometric monitoring has indicated that continuously saturated conditions exist 50–80 m below the slope surface (Figures 3 and 5), which is below the base of the active slope displacement zone. Seasonal piezometric variations of ≤ 20 m occur, are greatest towards the top of the continuously saturated rock mass, and progressively diminish with depth below the slope surface.

Monitored piezometric levels have displayed a direct response to precipitation, and to a lesser degree, seasonal snowmelt. Piezometric increases in the upper monitoring zones typically display a 12- to 18-hour time lag following significant precipitation, with a progressively longer time lag noted with increasing depth below the slope surface. Moreover, the magnitude of piezometric response to precipitation and infiltration/recharge is progressively smaller with increasing depth below the slope surface. These conditions indicate that the piezometric fluctuations are dominated by local infiltration, rather than by regional flow.

Piezometric levels display sharp increases associated with autumn-winter precipitation and spring snowmelt, followed by a general decreasing trend during spring to early autumn. Transient groundwater flow and pressures are interpreted to develop, particularly in the upper compartmentalized zones of the rock mass, and are considered to act as a trigger for the seasonal slope displacement cycles, based on the concurrence of increasing piezometric levels and the initiation of accelerated slope displacements.

Relative to the main slope area, the Checkerboard Creek channel has topographically downcut 80–90 m, and is topographically lower than borehole piezometric levels (Figure 3). Consistent seepage from the side walls of the creek channel has been observed. In contrast, seepage has generally not been observed on the exposed highway excavation, except during very short periods following seasonal snowmelt. These observations indicate that general slope groundwater flow is likely towards the creek channels (north/south), and not directly downslope (west). Moreover, these observations are consistent with the notion of compartmentalized groundwater, perched above and behind major geologic structures that impede downslope groundwater flow and sustain significant downslope groundwater gradients.

DISPLACEMENT BEHAVIOUR

Discussion of slope displacement behaviour focuses on the more reliable and accurate subsurface instruments. Surface monitoring results have been instrumental in establishing general displacement trends and areal displacement patterns, and serve to confirm observations in the subsurface instruments.

Subsurface slope displacements have been identified in inclinometer casings CC1, CC3, and CC4 to date, but not in CC6 and CC7. CC6 and CC7 thus provide easterly and southerly limits on the area of displacement, respectively.

The inclinometers indicate that displacements occur to depths of 50–55 m in the rock mass, with the following characteristics:

- Generally, the downslope displacement occurs diffusely throughout the rock mass, with the result that the surface moves more relative to the rock at depth, causing an overall downslope rotation (toppling).

- In CC3, an 8–10 m wide zone at the base of the displacing mass accommodates a considerable portion of the observed deformation (Figure 3); displacement below this zone appears insignificant.
- An overlying and relatively narrow zone, which indicates a reverse sense of displacement from adjoining zones, shows a relative "upslope" displacement direction, and is considered characteristic of a "toppling" deformation mechanism.

Thus, inclinometer data have revealed the slope movements to be characterized by a general downslope rotation (toppling) rather than block sliding or rotation along a continuous failure plane, an observation consistent with the observed drill core and surface geomorphology.

Displacements of 2 mm/yr in inclinometer CC1 indicate that slope displacement may extend below the level of Highway 23. These could be either an extension of the slope displacement recorded in the upper area, or a localized slope process below the level of the highway, independent of the larger upslope instability. A projection of the interpreted displacement zone from all slope instruments (Figures 3 and 4) suggests the former.

The most detailed record of slope displacement has been obtained from two multi-point borehole extensometers that monitor conspicuous surface tension cracks. These 60 m long sub-horizontal instruments provide a nearly continuous record of slope displacement, described as follows:

- Average annual displacements are 5–15 mm, occurring exclusively during an "active" phase from October to April of each year. Between May and September of each year, essentially no displacement has been recorded to date (Figure 5a).
- Subsurface thermistors have recorded insignificant temperature fluctuations in the rock mass. Assessment of thermistor and surface climatic information has indicated that slope displacement is not explained by temperature effects alone.

DISCUSSION OF DISPLACEMENT BEHAVIOUR

Slope monitoring since 1984 has revealed very slow displacements, with average downslope rates of 5–15 mm/yr. Monitoring has revealed a clear seasonal pattern to this movement, dominated by an active phase occurring in the late autumn to late winter, and a relatively inactive phase during the spring to late autumn period (Figure 5a). Careful scrutiny of the borehole extensometer records indicates distinctive variations in displacement rate, particularly during the "active" winter phase (Figure 5b). Sharp piezometric increases related to surface groundwater recharge from precipitation and/or snowmelt apparently trigger these accelerated displacement responses. Conversely, periods of prolonged piezometric level decrease, typical during summer to autumn, correlate with cessation of the displacements.

There does not appear to be a "threshold" precipitation or piezometric level required to initiate accelerated slope displacement. Isolated, high-volume precipitation during the May to September period has not initiated slope displacements, whereas more prolonged, but smaller-magnitude events in the October to April period typically initiate accelerated slope displacements. In terms of piezometric levels, accelerated displacements can be triggered by lower, but rising, piezometric levels, compared with higher, but falling, piezometric levels when slope displacements decelerate.

Inclinometer records also support the seasonal slope displacement cycles and relationship to increased piezometric levels and associated transient groundwater pressures. Initial displacement direction in each annual cycle is closely perpendicular to the strike of the primary discontinuities, up to 20° oblique to the downslope direction. Association of inclinometer displacement and increased piezometric pressures suggests a reduction in effective rock mass stresses leading to joint dilation and slip. Subsequent inclinometer displacements indicate a transition towards the downslope (gravitational) direction. As slope displacements decelerate with piezometric "discharge," the inclinometers have indicated a minor upslope "rebound," which again trends perpendicular to the primary discontinuity set.

The inclinometer profiles in CC3 and CC4 indicate that the displacement mechanics are governed by an overall downslope rotation, characterized as "toppling" along the steeply dipping discontinuities, with displacement rates greatest at the slope surface and progressively diminishing with depth (Figure 3). This observation is consistent with the array of surface tension cracks and absence of a through-going basal sliding surface.

The average annual rate of displacement has remained relatively uniform since 1984. To account for the widths of the tension cracks, similar slope displacements would have to have been active for at least hundreds of years, and more likely throughout much of the Holocene. Observations supporting this include the span of individual tension cracks (up to 4 m), the cumulative span across tension cracks in the central section of the slope (~10 m), large trees growing in the tension cracks, infilling deposits observed near surface and at depth in the tension cracks, and weathering and organic growth (moss/lichens) on the tension crack walls.

During excavation of the highway rock cuts in 1977/78, considerable backbreak of the designed rock cut benches occurred, which was attributed to the locally, highly weathered nature of the rock. Retrospectively, the excavation difficulties are interpreted to be indicative of the marginal slope stability conditions and the existence of a slow, active slope displacement process. Instrumentation data indicate that any remnant slope displacement triggered by the excavation had abated sometime prior to monitoring, based on the inactive displacement behaviour noted during subsequent summer periods. This does not imply that the highway excavation had no effect on the stability of the slope, only that any accelerated displacements that might have been triggered by that change are no longer apparent, as evidenced by the apparently inactive displacement behaviour in the summer periods.

Clear evidence from instrumentation data indicates that current slope displacement behaviour at Checkerboard Creek is not a remnant creep effect from either prehistoric causes or the recent highway excavation, but is related to the elevated groundwater conditions that prevail in the upper section of the rock mass during the winter months.

The current slope displacement process and the implications of slope failure highlight the importance of maintaining a comprehensive monitoring system, regular inspections, and ongoing, careful analysis of all instrumentation results. These activities are essential for developing a clear understanding of the slope behaviour and the related hazard of a landslide wave, and to detect any changes in slope displacement behaviour.

ANALYTICAL STUDIES

Numerical modelling studies using the computer code FLAC were carried out to forecast potential seismic and groundwater loading conditions. FLAC, based on an incremental finite difference approach, provided the capability to model displacements and the complex deformation process. Application of a limit equilibrium modelling approach was not considered appropriate, based on the lack of a basal sliding mechanism. Material properties for the model were based on the results of core logging observations and measured parameters, and compressive strength testing. This information was incorporated to establish rock mass and discontinuity properties, based on the Hoek and Brown (1997) and Bandis (1993) empirical approaches, respectively.

The results of the seismic analyses indicated the following:

- A simulated 1-in-1000-year seismic event (0.1 g) would generate displacements of less than 50 cm, which would not likely trigger slope collapse.
- Conversely, the 1-in-10 000-year seismic event (0.2 g) indicated displacements in excess of 10 m, which would be more likely to trigger slope collapse.

Investigation of groundwater conditions using FLAC indicated the following:

- Reservoir filling had no significant effect on the slope stability.
- A 50-m rise in the level of the continuously saturated rock mass above currently recorded levels would be required to cause slope collapse.
- A state of constant slope recharge and rising piezometric levels could generate significant downslope displacements, potentially leading to slope collapse.

Modelling of the long-term slope behaviour indicated that current displacements in the order of 5–15 mm/yr are likely to persist, provided that groundwater conditions continue to trigger the displacement cycles. The current, slow displacement process is forecasted to prevail until cumulative displacement potentially reduces overall rock mass strengths to levels that allow a change in deformation mechanics. In the absence of large seismic shaking, a change in slope displacement behaviour due to strength reduction is likely to provide indications that would be identified in the instrumentation network in the form of changing displacement rates and patterns.

SUMMARY

Displacement behaviour in the Checkerboard Creek rock slope is summarized as follows:

- About 3 million m^3 of rock is currently involved in a very slow, complex displacement process. Monitored displacements are greatest along the slope surface, progressively diminish with depth, include some zones of concentration, and are not detected below a depth of about 55 m.

- The interpreted displacement mechanism involves a complex interaction of dilation and slip along steeply dipping discontinuities, with offset across intersecting structures, resulting in a displacement profile characterized by overall downslope rotation of the deforming rock mass.
- Monitored displacements are spatially non-uniform across the slope surface, displaying an increase towards the centre of the mass, immediately above the highway cut.
- Displacements from 1993 to 2000 have indicated a seasonal pattern, comprising an “active” period between October and April, and an “inactive” period between May and September. Average downslope displacement rates range from 2 to 15 mm/yr, but occur almost entirely during the active period. The active period indicates the marginal stability of the rock slope.
- The observed seasonal displacement pattern clearly correlates with climatic conditions involving increased precipitation and infiltration during the active period. Slope displacements are interpreted to be primarily driven by transient groundwater conditions that develop above the long-term phreatic surface during periods of significant infiltration.
- Numerical modelling studies, using the computer code FLAC, have indicated that a significant increase in the long-term phreatic surface, some 50 m above currently recorded levels, would be required to cause slope collapse; such a scenario is considered highly unlikely.
- A condition of constant slope recharge and increasing piezometric pressures within the displacing mass could generate significant downslope movements, and could lead to slope collapse.
- Gradual degradation of the rock mass quality is expected to continue with ongoing slope displacement. Previous deterioration is seen in the drill core, and is largely confined in the currently displacing mass.
- Dynamic numerical modelling studies of the rock slope have indicated that seismic loading corresponding to the 1-in-10 000-year event, in conjunction with active period transient groundwater conditions, generates slope displacements of up to tens of metres and appreciable downslope velocities, which could lead to slope collapse.
- Reduction of the transient groundwater pressures may be a potentially effective measure in reducing slope displacements, and the risk of a seismically triggered collapse.

Possible remedial options are under consideration. In the meantime, a comprehensive ADAS with real-time monitoring and integrated alarms has been installed and is carefully monitored.

ACKNOWLEDGEMENTS

The authors would like to thank BC Hydro for the opportunity to pursue technical investigation and assessment of the Checkerboard Creek Project. Thanks are also due to Lori-Ann Wilchek for her helpful efforts in preparing the figures, and to B.D. Ripley for his helpful editorial suggestions.

REFERENCES

Bandis, S.C. 1993. Engineering properties and characterization of rock discontinuities. *In* Comprehensive rock engineering, principles and practice. J.A. Hudson (editor). Pergamon, Oxford, U.K. Vol 1., pp. 155–84.

Bovis, M.J. and T.W. Stewart. 1998. Long-term deformation of a glacially undercut rock slope, southwest British Columbia. *In* Proc. 8th IAEG Conf. D.P. Moore and O. Hungr (editors). Vancouver B.C., Sept. 21–25, 1998, Balkema, Rotterdam, Netherlands. Vol. II, pp. 1267–76.

Hoek, E. and E.T. Brown. 1997. Practical estimates of rock mass strength. Int. J. Rock Mech. Min. Sci. 34(8):1165–86.

Lane, L.S. 1984. Brittle deformation in the Columbia River fault zone near Revelstoke, southeastern British Columbia. Can. J. Earth Sci. 21:584–98.

Radbruch-Hall, D.H., D.J. Varnes, and R.B. Colton. 1977. Gravitational spreading of steep-sided ridges ("Sackung") in Colorado. J. Res. U.S. Geol. Survey 5:359–63.

Stewart, T.W. 1997. Investigation of rock slope deformation at the Wahleach hydroelectric project using the FLAC computer code. M.A.Sc. thesis. Univ. B.C., Vancouver, B.C.

Tabor, R.W. 1971. Origin of ridge-top depressions by large-scale creep in the Olympic Mountains, Washington. Geol. Soc. Am. Bull. 21:1811–22.