RAINFALL, PORE WATER PRESSURE, AND SLOPE MOVEMENT IN SILTS AND SHALES NEAR FORT ST. JOHN, BRITISH COLUMBIA

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ABSTRACT
Instability of Cretaceous shales and glacial silts impacts infrastructure in northeastern British Columbia. Airphotos reveal that most river valley slopes have experienced movement. Downslope movements near pipeline river crossings apply longitudinal stresses to pipelines resulting in compression at the slope base. Two study sites near Fort St. John have been instrumented to obtain continuous measurements of slope movement and pore water pressure to improve the correlation of these two elements with rainfall. Manual measurements indicate that movement rates range from 4 to 59 mm/yr. The shear zones are found in both shale and silt. Analysis of the continuous data indicates slope movements are closely timed to pore water pressure increases. This monitoring will be maintained to characterize the length of the delay between rainfall, pore pressure changes, and slope movements.

RÉSUMÉ
L'instabilité des schistes du Crétacé et des silts glaciaires a des impacts sur l'infrastructure dans le nord-est de la Colombie-Britannique. Les photos aériennes montrent que la majorité des pentes situées dans les vallées fluviales ont subi des glissements de terrain. Les mouvements du terrain sur les pentes où les pipelines traversent les rivières exercent une tension longitudinale sur les pipelines, ce qui résulte en une compression au bas des pentes. Afin d'améliorer la corrélation entre les précipitations, les mouvements du terrain et les pressions d'eau interstitielles, deux sites ont été choisis près de Fort St. John pour obtenir l'information de manière continue. Les mesures manuelles indiquent que les mouvements du terrain sont de 4 à 59 mm par année. Les zones de cisaillement se trouvent dans le schiste et dans le silt. Les données continues indiquent que les mouvements sont temporellement liés aux augmentations des pressions interstitielles. Cette surveillance continuera dans le but de caractériser le délai entre les précipitations, les changements de pressions interstitielles et les mouvements du terrain.

1. INTRODUCTION

Cretaceous shales and glacial silts and clays found in the oil- and gas-producing region of northeastern British Columbia are prone to sliding. Both large-scale, rapid landslides and slow, progressive slope movements have impacts on the region's extensive infrastructure including pipelines, railways, and highways. While catastrophic landslides can have an immediate devastating effect, gradual movements are disruptive to infrastructure as well. Airphotos reveal that most river valley slopes have experienced movement.

Downslope movements at pipeline stream and river crossings apply longitudinal stresses resulting in tension in the pipeline at the top of the slope and compression at the toe of the slope. Occasionally buckling and even rupture of a pipeline has occurred in the zone of compression. In such cases the pipeline is excavated and the affected length replaced. The preferred construction practice for pipelines is burial, however, in areas where slope movement is significant, pipelines have been placed above ground on timbers to enable the pipe to adjust more readily to displacement. Several cases of surface pipeline segments exist in northeastern BC such as along Duke Energy's 30" main line from Fort Nelson which has surface segments at four major creek crossings (McClarty and Cavers 1998).

To improve the accuracy of predicting gradual downslope movements, the Geological Survey of Canada (GSC) has installed instrumentation at two pipeline industry study sites in the Fort St. John area where several years of manual inclinometer measurements had been collected (Figure 1). Additional instrumentation since 2002 is allowing continuous displacement and pore water pressure monitoring. These studies seek to improve the understanding of the role that rainfall and snowmelt infiltration play in controlling slope movement. The ultimate goal of the work is to forecast pipe strains due to the progressive slope deformations. In support of this goal, it is necessary to establish the importance of pore pressure variations as a factor in controlling the mechanical response of slopes.

2. REGIONAL GEOLOGY AND INSTABILITY

The Peace River region is underlain by horizontal to gently northeasterly dipping Cretaceous shales and sandstones. The Dunvegan Formation, stratigraphically the highest bedrock unit in the region, is predominantly fine- to coarse-grained sandstone and conglomerate with lesser amounts of siltstone and shale, ranging in thickness from 100 to 300 m. Underlying the Dunvegan Formation are the marine shales and siltstones of the Shaftesbury Formation of the Fort St. John Group. Well records estimate the thickness of the Shaftesbury

Formation to range from 260 m to over 820 m (Stott 1982).

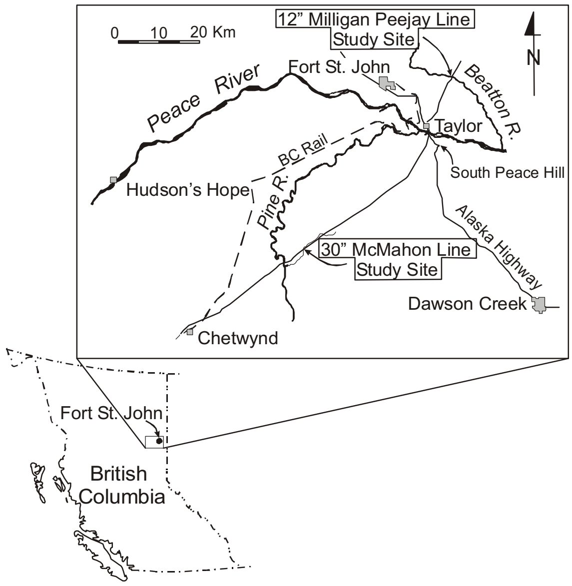

Figure 1. Location of study sites and communities referred to in the text.

During the Quaternary period, the area was subjected to at least three glaciations by Laurentide ice (Mathews 1978). Ice damming of the Peace River during at least two stages in the advance of the ice sheet resulted in the deposition of two separate units of glaciolacustrine silts and clays, each underlain by sands and gravels and overlain by till. The retreat of the ice resulted in a third glaciolacustrine unit being deposited atop the till (Mathews 1978). The Quaternary sediments overlie the Cretaceous units and are thickest in the pre-glacial river valleys where they can exceed 200 m.

The regional physiography is characterized by deep stream incisions into a gently rolling terrain. The Peace River and its major tributaries primarily occupy preglacial valleys, though the modern valleys are often narrower in width (Mathews 1978). In several instances, the present day rivers have cut into bedrock. Tributary stream valleys are typically narrow and v-shaped or have narrow flood plains, e.g. Beatton River. The valley of the Peace River is wider with several terrace levels. However, slopes are typically as steep as elsewhere especially where toe erosion is active. Slope characteristics are dominated by the underlying material (Mathews 1978) to the extent that the Dunvegan Formation supports the steepest slopes. Otherwise, where Quaternary strata dominate, slopes tend to be scalloped with steep upper portions and shallower lower portions representing slide runouts. Slopes in Quaternary materials average 25° but are subdued where they flank older terrace levels along the Peace River.

Within a 15 km radius of Fort St. John, 10 landslides or slope movements affecting infrastructure have occurred in the last 10 years. Except for short segments exposing Cretaceous bedrock, almost the entire length of the Beatton River exhibits slope failures. Landslides are also common along the Peace River although elevated terrace slopes often do not show clear evidence of slope failure. Regional airphoto analysis and radiocarbon dating of seven local slides indicate that slope failures have been frequent during at least the last several centuries. It is evident, therefore, that landslides will continue to impact the region’s infrastructure.

Several of the major slides that have occurred historically in the region have been described, including the Attachie slide of 1973 (Evans et al. 1996) and slides in similar geology found in northwest Alberta, such as the 1939 Montagneuse River landslide (Cruden et al. 1997) and the 1990 Saddle River slide (Cruden et al. 1993). These landslides are unique in that they occurred rapidly and resulted in a temporary damming of the river (Cruden et al. 2001).

Gradual slope movements are more difficult to detect but have been repeatedly revealed or re-activated by highway construction. Ongoing slope movements have affected a segment of the Alaska Highway known as “South Peace Hill” during the past 60 years (south approach to the Peace River Bridge near Taylor, see Figure 1). This grade has required continuous patching and drainage control, maintenance and clean up of slide debris, minor realignments and construction of granular berms and retaining walls. Maintenance costs for the period between 1986 and 1999 were $1.92 million. Accelerated movement has been linked to periods of increased rainfall. In the late 1990’s and early 2000’s, the British Columbia Ministry of Transportation and Highways (MoTH) conducted extensive geotechnical investigations including drilling, sampling, and testing as well as installation of slope inclinometers and piezometers. MoTH has determined the sliding to be at the soil-bedrock interface. Previous geotechnical investigations have revealed localized, perched water tables, considered contributory to instability (MoTH 1999). Several inclinometers indicate more than one shear plane. Movement data for selected slope indicators show that between spring 2000 and spring 2001, approximately 25 to 55 mm of displacement occurred (MoTH unpublished data).

The Cache Creek Hill is a segment of Highway 29, west of Fort St. John, that is prone to instability. According to a 1995 MoTH Geotechnical report, the Cache Creek Hill has had a long history of instability since original construction prompting geotechnical investigations beginning in the early 1980’s. Believed to be initiated by construction practices, the slides tend to be flow-like and shallow, and aggravated by wetter than normal conditions. Slope inclinometer data from 1988-1989 indicate a shear plane at 4 m depth in clay (MoTH 1989). A large slide area resulting from shearing through the shale bedrock is located adjacent to the alignment (MoTH 1995). Immediately north of Fort St. John, a section of highway traversing Quaternary sediments into the Beatton River valley required stabilization against movements also re-activated during construction (Polysou et al. 1998).

Pipeline distress in the Fort St. John area has resulted from gradual movements both in Quaternary sediments and the underlying Cretaceous bedrock. Two study sites are discussed in detail, the 12” Milligan Peejay gas pipeline crossing of Beatton River immediately north of Fort St. John and the 30” McMahon gas pipeline crossing of Stewart Creek 47 km southwest of Fort St. John (Figure 1).

3. SITE DESCRIPTIONS

The Milligan Peejay and Stewart Creek sites were selected for investigation based on their history of slope movement and effect on pipeline integrity. Both sites coincide with the pipeline right-of-way. The Milligan Peejay pipeline is a raw gas transmission line constructed in 1969 that runs from a gathering area 50 km north of Fort St. John to the Taylor processing plant southeast of Fort St. John. The monitoring site is located on the south approach slope to the Beatton River, 10 km NEE of the Fort St. John airport. The slope is characterized by a steep, 30 to 35^{o}, bedrock slope shallowing at the bottom to a gentle (2 to 12^{o}) colluvium slope descending to the Beatton River for a total relief of about 220 m (Figure 2). The upper part of the slope comprises approximately 1.5 m of fill over 4.5 m of glaciolacustrine clayey silt overlying 9 m of silty clay till over bedrock. The bedrock consists of the Dunvegan sandstones and shales overlying the shales of the Shaftesbury Formation. Slope indicator data indicates shearing in the shales of the Shaftesbury Formation.

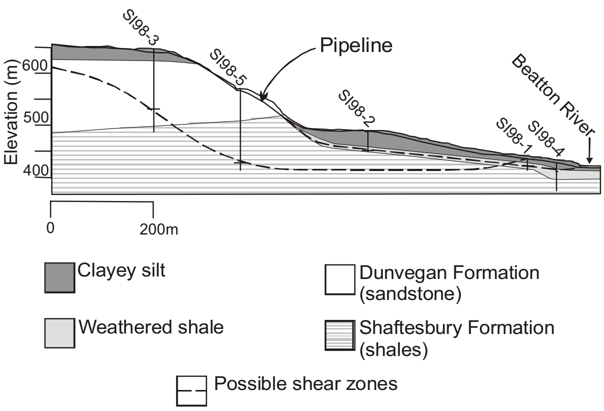

Figure 2. Cross-section of Milligan Peejay showing stratigraphy, slope inclinometer locations, and possible shear zones (after McClarty 2003).

The pipeline at the Stewart Creek site was constructed between 1955 and 1957 and has been subject to ground deformation since 1963 (AGRA 1996). The right-of-way originally consisted of an oil pipeline which was rerouted in 1977 following two failures at each of the creek approach slopes and a gas line which failed in 1979 near the toe of the south approach slope. Presently the only active transmission line in the Stewart Creek study site is the gas pipeline.

The geology at Stewart Creek is similar to that at Beatton with the cliff-forming Dunvegan Formation overlying the Shaftesbury shales. Both units are exposed along Stewart Creek. Overlying the bedrock is approximately 11 to 53 m of glacial silt and clay. The pipeline approaches Stewart Creek from the east across the slope before descending about 120 m on a 20° slope to the crossing. The site was first instrumented with inclinometers and piezometers in 1977, however, that instrumentation has since sheared off or been damaged and a second suite of instrumentation was installed in 2000. Several localized, slow-moving slides have been detected and a total of four slope inclinometer holes, 00-1, 00-4, 00-6, and 00-7, were chosen for use in the study. Three slides are under study at this site; 00-1 and 00-4 are located in the same slide which is moving parallel to the pipeline at the east approach to the creek while holes 00-6 and 00-7 are located in separate slides both moving transverse to the pipeline right-of-way. The maximum slope angle for each slide is similar at 20-23^{o}. Movement appears to be in the glacial silts and clays.

4. INSTRUMENTATION

The GSC instrumentation program augments the existing monitoring set-up at both study sites. The goal of the additional instrumentation is to gather continuous measurements of pore water pressure and ground movement in conjunction with manual measurements that are already underway. Existing inclinometer casings were instrumented with two in-place inclinometers suspended in tandem at locations where a prominent shear zone had been identified by manual inclinometer surveys. Each set-up is linked to a custom designed data logger programmed to take readings at six-hour intervals.

The locations of the in-place inclinometers in the casings are summarized in Table 1. Due to the multiple shear zones detected in the 00-7 manual data, the in-place inclinometers were suspended independently at the two lowermost shear zones. Continuous pore pressure measurements, corrected for atmospheric pressure variation, were initiated in multi-level Casagrande piezometers installed adjacent to the instrumented inclinometer casings at both sites. Water inlet levels are listed in Table 1.

5. CLIMATE

Fluctuations in pore water pressures resulting from rainfall and snowmelt infiltration are assumed to be fundamental in controlling slope movements at the study sites. A rainfall-slope movement correlation has been empirically demonstrated for gradual slope movements in the region (Konuk et al. 2002) and the present study serves to further quantify the pore pressure-movement relationship. Although no precipitation data has been collected at the sites, climate data is available for locations in the area. Climate data from Fort St. John airport is considered representative of conditions at the Milligan Peejay site, 10 km to the east. Based on Environment Canada's climate normals for 1971-2000, the mean total annual precipitation is 466 mm with 313 mm falling as rain. The highest levels of precipitation occur during the months of June and July. Total snow accumulation is 186 cm, which is on the ground normally from October to April. Typically, the snow has melted by the end of April. Mean monthly temperatures rise above 0^{o}C starting in April and dip below freezing in November.

Table 1: Monitoring Details

Site	Bore-hole No.	Shear Plane Depth (m)	Depth of Monitoring (m)	Piezometer Tip Depth (m)
Milligan Peejay	98-1	15.0	14.0 – 15.2	4.3, 14.8, 22.5
	98-2	36.7	36.5 – 37.8	4.3, 25.4
Stewart Creek	00-1	12.7	12.0 – 13.0	6.2, 12.2, 36.4
	00-4	15.9	15.6 – 16.6	10.6, 18.8, 43.5
	00-6	51.0	51.0	30.2, 50.9, 70.6
	00-7	16.5, 21.3	16.5, 21.3	7.7, 22.1, 29.2

The Stewart Creek site is located 47 km southwest of Fort St. John airport, hence is less well represented by the airport data. To determine the variability in precipitation in the area, the record between 1982 and 2002 from the Fort St. John airport was compared with that from Chetwynd airport (83 km SW of Fort St. John), Taylor Flats (10 km SSE), and Dawson Creek airport (65 km SSE). Compared over 20 years, the precipitation data for the four stations is fairly consistent in trends and amounts. The four most recent years of record, including Hudson Hope (76 km SW), are similar with the lowest precipitation occurring in October through April and maximum amounts during June and July. However, the amount of precipitation is variable among the stations during the months May to September, the months of greatest rainfall. The largest discrepancy occurred in July 2001 between Fort St. John, 71 mm, and Dawson Creek, 146 mm. Linear regression of the Fort St. John precipitation between 1999 and 2002 with each of the above mentioned stations indicates that from May through September rainfall can be quite variable. Taylor Flats, the closest station to Fort St. John, gives an R^2 value of 0.90. However, the R^2 values for correlation with Chetwynd, Dawson Creek, and Hudson Hope are 0.40, 0.48, and 0.52, respectively. Comparison of each station with the others indicates a range in correlation values of 0.58 to 0.74. Due to the overall variability among the stations, the lack of precipitation record for the Stewart Creek site itself, and the completeness of record available from the Fort St. John Airport, the Fort St. John record was used in this analysis of the Stewart Creek site data as well.

6. SHEAR ZONE MOVEMENT

Manual inclinometer readings are plotted for Milligan Peejay since 1998 (Figure 3). Data for holes 98-1 and 98-2 indicate a discrete shear plane at 15 m and 37 m, respectively (Figure 4). The total displacements measured at the shear zone for 98-1 and 98-2 were 36 mm and 58 mm, respectively, before the casings in both were sheared in 2001. Replacement casings were installed adjacent to each hole and continuing displacements along the previously identified shear zones added to the original record. The displacement records in Figure 3 show an overall continuous shearing punctuated with intervals of accelerated movement. When compared with the superimposed cumulative precipitation for Fort St. John, there is a visual correspondence between shearing accelerations and accelerated rainfall accumulations (Figure 3). For example, the data for 98-1 indicate an increase in movement at three specific intervals: mid-March and mid-July 2001, mid-March and mid-July 2002, and mid-February and late-June 2003. The increases in precipitation intervals are: May to September 2000, April to July 2001, June to September 2002, and May to August 2003. Due to an interval of months between certain manual readings it is difficult to know whether the movement was constant or occurred abruptly at the beginning, middle or end of the interval, thus correlation with the essentially continuous precipitation record is hindered. Linear regression of movement and precipitation yields a correlation which can only be markedly improved by correlating the movement increments with rainfall increments almost a year earlier. As both parameters appear to have an annual cyclicity, it is most likely that the shear zones are reacting within a month rather than a year to either rainfall increases or the onset of snowmelt infiltration. The same conclusion applies to the analysis of manual inclinometer measurements from the Stewart Creek site.

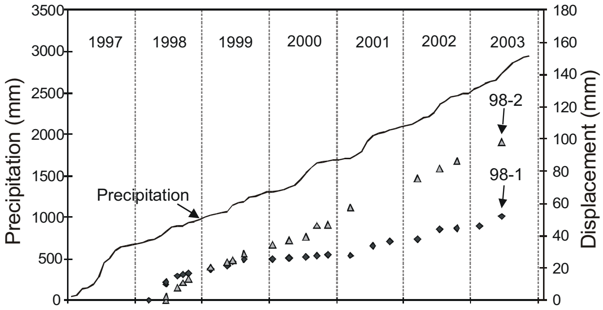

Figure 3. Cumulative precipitation and displacement from 1997 to 2003 for Milligan Peejay.

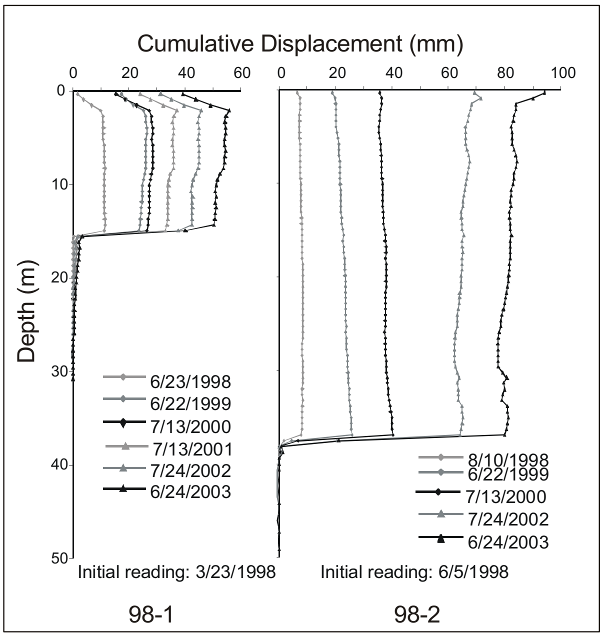

Figure 4. Plot of cumulative displacement for Milligan Peejay inclinometers, 98-1 and 98-2.

The continuous inclinometer and piezometer records, though limited to less than a year (4.5 months for 98-1 and 9 months for 98-2), provide insight into the timing of ground movement. Of particular interest is the record for 98-1 as it shows little movement since installation, February 15, 2003, followed by a marked increase in movement starting April 23, 2003 with movement continuing until time of download, June 24, 2003 (Figure 5). The data for 98-2 is less straightforward; movement appears to be occurring throughout the monitoring period, however, a slight acceleration is noted around April 30, 2003.

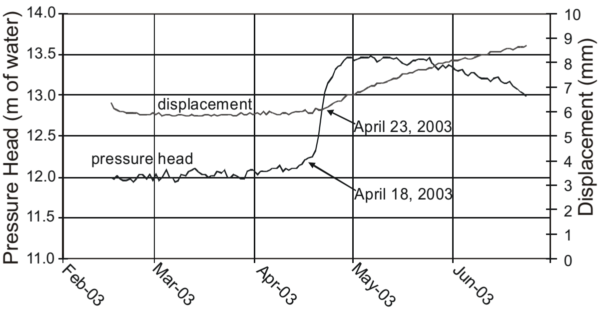

Figure 5. Continuous pressure head, measured in metres of water, and ground displacement for Milligan Peejay location 98-1.

At the Stewart Creek site, manual inclinometer measurements are available since 2000. The slope inclinometer data indicates one discrete shear zone in each of the 00-1, 00-4 and 00-6 boreholes. Hole 00-7, which was subsequently replaced in 2002 due to excessive shearing, displays at least 3 shear zones (Figure 6). Total displacement at the deepest shear zone (21.3 m) in inclinometer 00-7 is 109 mm (258 mm at surface). The total amount of movement observed in holes 00-1, 00-4 and 00-6 is 21 mm, 28 mm, and 10 mm, respectively.

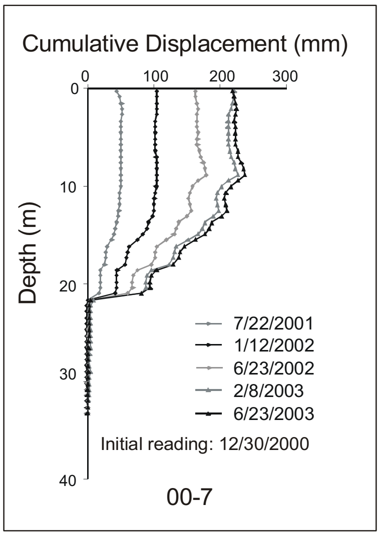

Figure 6. Cumulative displacement indicating the multiple shear zones in Stewart Creek inclinometer 00-7.

Similar to Milligan Peejay, the movement record for 00-7 shows periodic accelerations. These episodes occur between the manual readings of April 22 and September 9, 2001, February 28 and June 23, 2002, and February 2 and June 23, 2003. Readings are less frequent for the other three inclinometers, making correlations less obvious.

A nine month, mid-September to mid-June, continuous record of movement is available for the in-place inclinometers at Stewart Creek. Generally, the in-place records are comparable to the manual records in relative magnitude, with 00-7 showing about 4 to 8 times as much movement as the other three inclinometers. However the in-place records are too short to make further comparisons between manual and continuously recorded data.

7. PORE PRESSURE VARIATION

Presently, a correspondence between pore pressure variation and changes in shear displacement rate is only clear for the Milligan Peejay site. Initiation or acceleration of displacement within a few days of pore pressure increases is seen for 98-1 (Figure 5) and 98-2 exhibits a 15-day delay. At Stewart Creek there is no obvious pore pressure-displacement correspondence. Displacement for all in-place inclinometers at Stewart Creek is occurring steadily with minor variations in rate for all shear zones instrumented. There is a slight increase in shearing rate in April or May for all but one inclinometer at Stewart Creek but this does not bear any relationship to pore pressure changes. For the most part, pore pressures are constant but certain piezometer levels contain no water. The Stewart Creek site is typified by apparent perched water tables, as revealed by dry conditions in piezometer nests 00-1 and 00-6. In general, water levels tend to be very low in the three piezometers located on the steep slope to Stewart Creek, in accordance with the steep drainage gradient as would be expected in such a setting. The only pore pressure response that is comparable to Milligan Peejay is for the shallowest level at 00-1 where a prominent pressure increase begins in early April.

8. DISCUSSION

Although short in duration, the supplementary continuous measurements of movement and pore pressure from the two pipeline slopes demonstrate that the movement rate along shear zones at the two sites is probably controlled by pore water pressure. The relation between pore pressure and precipitation is less clear, primarily because there is no measure of infiltration at the sites.

Fort St. John weather records for 2003 indicate that the mean daily temperature rose above freezing starting April 7th and that the snow on the ground had started melting March 17th and was gone by April 20th. Elevation of pore water pressures, therefore, occurred less than a month following the melt period at both sites, e.g. Figure 5. Where some piezometers showed either little fluctuation or a decline in pore pressure, it can only be concluded that part of the groundwater flow system, in particular at Stewart Creek, is hydraulically isolated and only responds to greater infiltration than occurred in 2003 or on longer time scales than covered by these observations.

Groundwater flow is probably fundamental in the control of slope deformations in the Fort St. John area. A two-dimensional groundwater flow simulation was carried out to give an approximate indication of pore pressure variability that could be expected, given the annual variability in precipitation. Based on examination of water well records for the Fort St. John area, a steep downward hydraulic gradient exists beneath the uplands extending back from the Peace River and its tributaries. Widespread basal gravels of the Quaternary sequence (Mathews 1978) may act as a drain for discharge to low levels in the river valleys. Similar steep gradients exist in the Dunvegan Formation, based on the piezometer observations at the two study sites. Perched water tables are probably typical in the Cretaceous units, given the interbedding of shaly and sandy strata, existence of springs at various levels on valley sides, and the multi-level piezometers with the lower levels dry. Major infiltrations may result in pore pressure rises at several levels if infiltrating water is intercepted at different perched water tables.

A geological cross-section was prepared based on the interpretation of drill records for the Milligan Peejay site (McClarty 2003) and DC-resistivity profiling (Calvert et al. 2004). Although infiltration measurements are not available, an estimate can be made using Water Survey of Canada stream gauge records that are available for sites with relatively small catchments (i.e. <100 km^2) in the region. The hydraulic conductivity of the groundwater model is adjusted to produce a discharge that matches a selected baseflow for the stream basin analyzed. Groundwater flow in equilibrium with a specified infiltration was determined for two infiltration rates: 180 mm per year representing moist conditions and 15 mm per year for dry conditions. Although equilibrium is probably never achieved, the two cases indicate the variability in groundwater flow that may occur in the valley-side settings of the Fort St. John area.

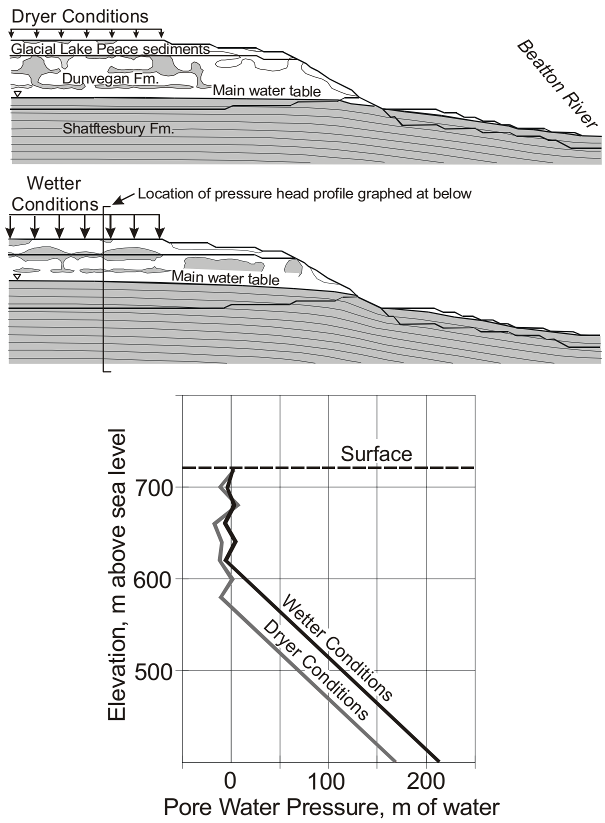

Figure 7. Cross-section of Milligan Peejay site showing pressure head distribution (pressure head contour interval: 20m, grey shading indicates positive head) in equilibrium with an annual infiltration of 15 mm (Dryer Conditions) and 180 mm (Wetter Conditions). Graph below shows pressure head distribution with depth at the location denoted on cross-section.

Pressure head distribution for equilibrium flow under the two infiltration rates is shown in Figure 7. Seepage from the base of the Dunvegan Formation coincides with a high conductivity zone detected at the same location by the DC-resistivity survey. The main hydraulic difference is the large variation in water table elevation between the two cases. Possibly as significant is the decrease in thickness of the zone above the water table. The Dunvegan Formation is represented as having homogeneous and isotropic hydraulic conductivity. However, the variation in pressure head, from slightly above to slightly below atmospheric, in the zone above the water table suggests that perched water table formation would be favored if any variability in vertical hydraulic conductivity was present. The implication for slope stability is that drops in effective stress beneath perched water tables may occur throughout the zone above the main water table as well as below the water table.

9. CONCLUSION

Historic records, airphoto analysis, and radiocarbon dating indicate that both rapid and slowly moving landslides in glacial deposits and underlying Cretaceous shale are ongoing phenomena in the Fort St. John area. Continuous recording of displacements and pore pressures at two sites where slope movements affect pipeline maintenance has demonstrated that slope movement accelerations are closely timed to pore pressure increases. The observations for these sites are preliminary since less than one year of data is presented here. However, these sites will be maintained until the response to several yearly climate cycles has been recorded so that a more general indication of mechanical behavior can be determined. At the same time, the understanding of slope movements and the implication for pipeline integrity will be advanced on other avenues. These include the measurement of displacements between a pipe and surrounding soil as well as development of slope deformation simulations that will be in part guided by deformation characteristics inferred from the present monitoring program.

10. ACKNOWLEDGEMENTS

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