Characterization of creep movements at the Little Chief Slide, BC

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ABSTRACT

The 900 million m³ deep seated Little Chief slide has been moving on thin gouge layers with an average rate of 14mm/yr. Geological history of the glacial till underlying the slide toe and examination of some ash deposits indicated that the initial movement occurred approximately 60000 years ago. Since 2004, an extensive field program has been carried out that included drilling eight boreholes averaging 325m in depth and instrumented with inclinometers and piezometers in addition to surface monuments. Rainfall and reservoir level fluctuations do not correlate with slope movements. Hence an experimental triaxial creep program has been carried out on some of the available undisturbed cores to explore the relation between laboratory and field creep rates. The results agreed with the well known Singh Mitchell equations. The level of field shear strain rates observed was comparable to the laboratory values investigated.

RÉSUMÉ

Les 900 millions de m3 profond Little Chef de diapositives a été de passer des couches minces rainures avec un taux moyen de 14mm/yr. Histoire géologique du till glaciaire qui sous-tendent la diapositive orteil et de l'examen de certains dépôts de cendres a indiqué que le mouvement initial est survenu environ 60000 ans. Depuis 2004, un vaste programme sur le terrain a été menée qui comprenait des forages huit forages en profondeur moyenne de 325m et instrumenté avec inclinomètres et piézomètres de surface en plus de monuments. Précipitations et les fluctuations du niveau des réservoirs ne sont pas en corrélation avec les mouvements de pente. C'est pourquoi un programme expérimental de fluage triaxial a été effectué sur certains des carottes non perturbées disponibles pour explorer la relation entre le laboratoire et sur le terrain des taux de fluage. Les résultats d'accord avec le bien connu Singh Mitchell équations. Le niveau de contrainte de cisaillement du terrain a été observé des taux comparables aux valeurs de laboratoire étudiés.

1. Introduction

The Little Chief Slide is on the Northwest side of the former Columbia River valley in the Monashee Mountains. The valley at this location is about 1425m deep and has an average slope of about 30°. The construction of the Revelstoke and Mica Hydroelectric projects on the former Columbia River had resulted in considerable rises in the water levels behind the dams forming reservoirs (Figure 1). This rise caused inundation of the toes of many ancient rockslides one of which is the Little Chief Slide. The stability of these slides is a major design, reservoir operation and safety requirement.

The current rate of movement in the Little Chief Slide is around 10 to 14 mm/year. The slide is thus classified as an extremely slow slide. The first time slide appears to have occurred thousands of years ago and the current movements are post-failure movements. The Little Chief slide is presumably moving as one entity evidenced by the equal rate of movement observed at many surface monuments along the slide. The movement zones support depths of rock ranging between 100 and 300 meters (Moore et al., 2006).

The site has been under investigation since the 1960's and recently since 2004. The paper presents the history of site investigation of the Little Chief Slide followed by an explanation of the site geology. The available historical information about the slide has led to the understanding that the creep properties of the materials forming the shear plane are responsible for the extremely slow movement. The results of an experimental creep testing program are presented. The laboratory strain rates were compared to some available records from the field.

2. Previous and Current Investigation

The Little Chief slide was identified during an airphoto study of the proposed Mica Dam reservoir in 1961. The initial investigation of the site started in 1968 and 1969 during the construction of the Mica Dam (1968 - 1970). There was a concern during the initial investigation that the toe of the Little Chief Slide rests on liquefiable sand. However, the subsurface investigation and monitoring program showed that such sand did not exist beneath the toe. The results of the investigation program indicated a uniform movement rate ranging between 4 and 14 mm/year even after reservoir filling. The inclinometers installed at that time were not able to penetrate deep shear planes and reliance was primarily on surface monuments. Enhanced inclinometer instrumentation in 1976 revealed a movement rate of 10 mm/year. BC Hydro found, however, that the previous investigation program neither gave a complete image of subsurface conditions nor did it provide sufficient information to predict the slope's behaviour especially under the effect of earthquakes. Consequently, a new extensive subsurface investigation and monitoring started in 2004. The current investigation by BC hydro is aimed at:

1- Studying stability under seismic loading,

- Better development of the geologic and hydrologic models,
- 3- Understanding the mechanics of slope movements, and
- 4- Determination of the risk of failure.
 - (Moore et al., 2006)



Figure 1: Location of Mica Dam and Little Chief Slide (Source: Moore et al., 2006)



Figure 2: Locations of the Boreholes Drilled in 2005

The current investigation program involved drilling eight new boreholes with an average depth of 325 meters in addition to the seven already existing boreholes. The new boreholes are fully instrumented by either inclinometers or piezometers so as to get full knowledge about the subsurface behaviour. Figure 2 shows the locations of the boreholes drilled in 2005.

An adequate hydrogeological model involves determination of the effect of reservoir filling and climate cycles on the ground water pressures and hence stability. In the current program, three holes at the shoreline, midway up the slope and high on the slope were equipped with 66 piezometer zones in addition to obtaining piezometric profiles in another six holes. The presence of the low permeable shear zones caused pressure differentials up to 75 meters between the overlying and the underlying materials. The effect of the reservoir filling cycle was found to be minimal especially for water pressures above the reservoir water level where the annual fluctuation was found to be a small fraction of the reservoir water level difference. The small fluctuations in water pressures at high locations on the slope are mostly attributed to annual climatic changes rather than reservoir filling cycle. The exact impact of climate on ground water pressure changes might be detected by the recently installed In Place Inclinometers (IPI) as time goes on.

Inclinometer results showed two distinct movement zones near the reservoir shoreline, four zones were detected near midslope, and only one zone was detected in higher inclinometers. However, the total movements detected at the surface of each hole were found to be practically equal.

3. Quaternary Geology and History of Movement

The toe of the slide had overridden the Quaternary deposits of glacial till and sand and gravel. The stratigraphy in one of the drill holes showed two glacial till units separated by a 22 meters thick layer of rock-slide deposits (Moore et al., 2006).

The previous geological interpretation revealed that the slide occurred at the end of the most recent glaciation and overrode the resulted glacial deposits. This interpretation implied that the slide occurred less than 11000 years ago. On the other hand, the current geological investigation suggests that the overridden till that lies below the valley floor and rests directly on bedrock is more likely associated with older glaciation that ended approximately 60000 years ago. Furthermore, some surface ash deposits (Mazama ashes) whose age dates back to 7700 years had not been disturbed by slide movement. Hence it is currently believed that this slide movement started at least some 60000 years ago, and no substantial movement had occurred for 7700 YBP (Moore et al., 2006).

4. Structural Geology

Moore et al. (2006) presented a brief summary of the structural geology of the Little Chief Slide. The materials encountered at the slide are Upper Proterozoic metasediments that have been deformed possibly four times. The metamorphism of these materials has led to the formation of minerals that are between garnet and sillimanite grade. A regional normal fault trends along the toe of the slope under the valley bottom. This might have caused a 1500m offset in stratigraphy. The faults underlying the base of Little Chief Slide have been possibly formed due to the potential existence of the regional normal fault.

There was evidence for only two of the four possible deformations recognized regionally. These are evidenced by the pervasive foliation and by a regional antiform adjacent to the northeast scarp and by minor folds elsewhere. The second deformation is also associated with lineations that usually plunge nearly down slope. However, some lineations plunge towards the opposite direction within an area that extends to about one third the slide width along the reservoir shoreline. This implies the possible occurrence of block rotation within the Slide. Joints usually dip along micaceous foliations and run parallel to the lithological boundaries. An exposure of a major tectonic fault was observed at the reservoir level downstream the slope. Another one was identified in the head scarp. Both dip steeply into the slope and may significantly alter the groundwater flow regime.

5. Nature of the Slide Materials

The high quality drilling techniques enabled better characterization of the slide deposits. The slide deposits range from soft, sheared micaceous material to hard fractured rock which is different from the underlying rock. Foliations within some blocks were uniform indicating limited internal deformations. These blocks were sometimes similar to the underlying rock which led to terminating the drilling at depths shallower than the rupture surface. This caused some misinterpretations.

The soft zones are mainly soft, granular or micaceous, enclosing some hard rock fragments. Shear zones containing thin clay layers are characteristic of the soft zones. The main rupture surface, or the basal detachment, is identified by the presence of slickensides and clay from a few millimetres to about 200 mm thick, followed by a suddenly-increased-quality rock. Although the underlying rock is sometimes fractured and sheared, these fractures and shears are tightly interlocked or intact.

Several consolidated-undrained triaxial and direct shear tests have been carried out to determine the shear strength of the softer materials. High Montmorillonite content was encountered in a few locations and has resulted in a residual friction angle of 10° . The majority of the tested samples yielded residual friction degrees between 22° and 31° . Peak strengths were either the same as residual or a little higher (Moore et al., 2006).

6. Characterization of Movement at the Little Chief Slide

The results of ground water monitoring for the Little Chief slide that have been available since 2004 and are summarized in section (2) of this paper show tentatively that the reservoir fluctuations have little or no effect on the extremely slow ongoing movements. As the movement zones at the Little Chief slide are 100 to 300 meters deep, the effect of rainfall on pore pressure changes along the movement zones could be considered minimal as well. A more detailed ground water flow modelling study will be carried out as part of this research project and the results will judge the reliability of this understanding.

Since the slide velocity is independent of the hydrological boundary conditions changes as evidenced from the available instrumentation results, the creep properties of the materials forming the slide plane seem to be responsible for the ongoing movements. From this base point, we started a drained creep testing program in order to characterize the time dependent behaviour of the slide materials.

As outlined by Ladanyi (1972), most of the creep theories can be categorized into two main approaches:

micro-mechanistic and macro-analytical. The micromechanistic approach deals with the creep behaviour at the particle interaction level while the macro-analytical approaches are based on macroscopic experimental findings that fit to certain mathematical equations. Although the former approach is derived from physical theories, it involves many parameters that are generally hard to evaluate from traditional testing procedures. However, the equations in the latter approach consist of a simple and small number of parameters that are easy to obtain from routine experimental testing (Ladanyi 1972 and Watts 1981).

The focus will be on the second approach; the macroanalytical or the phenomenological approach since it usually involves the evaluation of smaller number of parameters and proved to be reliable from previous research. Of the best phenomenological equation to describe creep behaviour in the laboratory is that derived by Singh and Mitchell (1968). The equation could be written in the following form:

$$\dot{\varepsilon} = A * e^{\bar{\alpha}\bar{D}} * \left\{\frac{t_i}{t}\right\}^m \tag{1}$$

where;

ε is the axial strain rate in a triaxial test (usually in laboratory expressed in %/min),

A is the axial strain rate at zero deviatoric stress at unit time (same units as strain rate),

 α is the slope of the logarithm of strain rate versus deviatoric stress level (should be constant for different times),

D is the deviatoric stress level (unitless),

 t_i is the initial testing time (usually set to unity in laboratory testing), and

t is the elapsed testing time (usually minutes in laboratory testing).

The advantages of Singh and Mitchell (1968) model are:

- 1- The equation is applicable to a wide range of stress levels (from 30% to 90%).
- 2- It describes the behaviour of a range of clays whether the clay is undisturbed or remoulded, normally consolidated or overconsolidated, or drained or undrained.
- 3- The equation is composed of three parameters that are easily determined from routine triaxial testing provided enough time is allowed for each increment in order to investigate time effects.

However, most of the previous creep studies dealt with stresses that are encountered in the near surface soil mechanics. It is not clear whether the model will fit the results of creep testing under high stresses as is the case of the Little Chief slide. One of the objectives of our experimental program is to determine whether the results will fit to the Singh-Mitchell equation or not.



Figure 3: Cross Section AA Showing the Location of Borehole DH05-07

7. Drained Triaxial Creep Testing Program

The characterization of time dependent soil deformation under high stresses at the Little Chief Slide is to be achieved through a drained triaxial creep testing program in addition to analyzing the field movement data. A ISCO Series D (model 100DX) single syringe pump was utilized to apply high stresses to the tested samples. The pump can be operated in either a pressure or a flow mode. The advantage of the flow mode is the ability to gradually increase the stress to a desired high value rather than increasing it suddenly if the pressure mode is switched on. The loading pump is explained in more detail elsewhere (Su, 2005). Some of the available undisturbed cores from the movement zones were considered for testing and are listed in Table 1. Plan locations of the boreholes are shown in Figure 2. Figure 3 shows the location of borehole DH05-07 with respect to the Mica Dam reservoir. Borehole DH05-06 is approximately 380m upstream of DH05-07 and is 38m apart from the toe of the slide. There was a continuous undisturbed core from depth 125.00 to 126.25 meters in borehole 05-07, so it was decided to perform three triaxial drained creep tests with different confining stresses (1.50 to 3.00MPa) to explore the effect of confining stress on the deformation rate. A photo of the samples taken at depth 125 -126.50m from DH05-07 is shown in Figure 4. Grain size distribution for the first three samples is plotted in Figure 5.



Figure 4: Photo of the Samples taken from DH05-7 between Depths of 125 and 126.50m (BC Hydro, 2005)

Table 1: Summary of Samples Information

Sample Number	Borehole	Depth (m)	Confining Stress (MPa)	
1	05-07	125.00 – 125.25	1.50	
2	05-07	125.50 – 125.75	2.00	
3	05-07	126.00 – 126.25	3.00	
4	05-06	171.05 – 171.25	4.62	
5	05-07	158.70 – 159.00	4.30	



Figure 5: Grain Size Distribution Curves for Samples 1 through 3

Figure 6 shows a sample of the results of the axial strain rate versus time plots for sample #2 from Borehole DH05-07, depth of 125.50 – 125.75m, tested at a confining stress of 2.0MPa. As shown in the figure, the axial strain rate plots at different deviatoric stress levels fit

8

well to a Singh-Mitchell creep equation (Singh and Mitchell, 1968). The slope of the axial strain rate – time plots is the creep parameter m which represents the deceleration of movement ranged between 0.872 and 1.172. Close examination of the D=3.7MPa plot in Figure 6 indicates tertiary creep occurrence following the primary stage with no secondary stage noted. This has a physical significance with respect to the expected level of stress that will be associated with acceleration of movement. The values of the parameter m resulted from each stress level are listed in Table 2.



Figure 6: Axial Strain Rate versus Time at Selected Testing Times only for Sample DH05-07: Depth 125.50 – 125.75, $\sigma_3 = 2.0MPa$.

Table 2: Values of the Creep Parameter m for Different Stress Levels for Sample DH05-07: Depth 125.50 – 125.75, $\sigma_3 = 2.0MPa$.

Deviatoric	Deviatoric	Creep	
Stress	Stress	Parameter	
(kPa)	Level*	(m <i>)</i>	
1042	0.186	1.172	
1838	0.327	1.189	
2665	0.475	1.000	
3701	0.659	0.872	

*See Table 4 for the value of Deviatoric Stress at failure

The values of the creep parameter m match well the above understanding. It is known that by integrating Singh-Mitchell equation the movement accelerates when the parameter m is less than one and decelerates when m is more than one (Liingaard et al. 2004, Augusteen et al. 2004 and Singh and Mitchell 1968). Based on the results of sample #2, a deviatoric stress level of 0.475 is the limit for strains acceleration. The drained creep behaviour at a confining stress of 2.0MPa could then be represented by the following Singh-Mitchell equation:

$$\dot{\epsilon} = A * e^{\bar{\alpha}\bar{D}} * \left\{\frac{t_i}{t}\right\}^m = 0.0724 * e^{2.832\bar{D}} * \left\{\frac{1}{t}\right\}^{1.058}$$
 (2)

The results of triaxial drained creep tests on sample #1 showed a similar behaviour and the axial strain rate function could be represented as well by an equation of the Singh-Mitchell type:

$$\dot{c} = A * e^{\bar{\alpha}\bar{D}} * \left\{\frac{t_i}{t}\right\}^m = 0.0022^* e^{2.36\bar{8D}} * \left\{\frac{1}{t}\right\}^{1.184}$$
 (3)

The values of the parameter m for deviatoric stress values of 0.50, 1.04, 1.55 and 2.19MPa were 1.040, 1.193, 1.310 and 1.192, respectively. Based on the above discussion the creep behaviour is mainly primary and movement is decelerating.

During the consolidation phase of sample #3, distinctive shear planes were found, so it was decided to re-constitute the sample by compacting it to its initial moisture content (~12.4%) and density and then leaving it in the moisture room to mature. The results of creep tests on sample #3 results (reconstituted sample) fitted the Singh-Mitchell equation as well. The creep behaviour was mainly primary as sample#1 and no strains acceleration was noticed. The Singh-Mitchell equation parameters for the first three creep tests are summarized in Table 3.

This summary shows an increase in creep parameters

A and α with increasing confining stress for samples #1 and #2. This would imply an increase in axial strain rate with confining stress. However, the results of sample #3 do not verify this trend. Generally, more than three samples need to be tested in order to be able to develop a modified Singh-Mitchell equation with confining stress dependent parameters. Samples 1 through 3 were loaded to failure after the end of the last creep increment. Table 4 presents the values of principal stresses at failure as well as the internal friction angles.

Table 3: Summary of Creep Equation Fitting Parameters Values

Test Confining # Stress		m		A (%/min)	_α			Remarks	
"	(MPa)	Range	Avg.	SD		Range	Avg.	SD	
1	1.5	1.04 – 1.31	1.18	0.11	0.0022	1.871 – 3.156	2.368	0.69	
2	2.0	0.87 – 1.19	1.06	0.15	0.0724	2.462 – 3.201	2.832	-	Tertiary creep observed at stress level 65.9%
3	3.0	0.86 – 1.22	0.97	0.17	0.0048	0.610 – 3.340	1.851	1.38	

Table 4: Summary of Failure Stresses and Friction Angles Values for Samples 1 through 3

Sample #	Confining Stress (MPa)	Deviatoric Stresses Applied During Creep Testing (MPa)	Deviatoric Stress at Failure (MPa)	Maximum Applied Deviatoric Stress Level (%)	Major Principal Stress (MPa)	Friction Angle (Degrees)
1	1.5	0.50, 1.00, 1.60, 2.20	2.50	88	4.00	27.04
2	2.0	1.04, 1.84, 2.67, 3.70	5.61	66	7.61	35.72
3 (Re- constituted)	3.0	2.80, 3.60, 4.40, 5.20	9.28	56	12.28	37.40

The summary shown in Table 4 indicates that the average friction angle at failure of the slide plane materials at borehole DH05-07 at a depth of approximately 126m equals 31.4° excluding the results of the re-constituted sample (Sample #3). The ground surface inclination at the location of borehole DH05-07 is approximately 16.8° (See Figure 3). Assuming infinite slope conditions, the shear stress level in the field would be 49.4% and the factor of safety against slope failure is around 2.

Sample #4 was chosen from borehole DH05-06 at a depth of 171.05 to 171.25 meters. The sample was intended to be loaded isotropically to its in-situ stress value (171.15X0.027 = 4.62MPa) then loaded until failure. The sample was consolidated to the design confining stress in increments as above. However, during the last increment, 2500 to 4620kPa, leakage was observed from the system and it was necessary to replace the cell. When the sample was removed, there were two distinct planes of failure. The sample included a detachment surface between rock-slide deposits and a soft clay seam. Therefore, although loading was isotropic, the material was not isotropic in response due to its heterogeneity.

Sample #5 lies at a depth of 158 meters in borehole DH05-07. The design confining stress is 4.3MPa. One of the purposes of testing sample #5 is investigating the creep behaviour under very low deviatoric stress levels. Singh and Mitchell (1968) found the creep strains under deviatoric stress levels less than 30% to be of little practical importance. However, they based their conclusion on tests carried out at relatively low confining

stresses. Sample #5 was subjected to very low deviatoric increments of 500 and 1000kPa. The results of axial strain versus time for the D=1000kPa increment was very noisy and suggested the occurrence of a technical problem with the LVDT. Figure 7 shows the axial strain rate versus time plot for the D=500kPa increment. The value of the creep parameter "*m*" is well below the expected range for most soils (Singh and Mitchell, 1968). This suggests that movements at very small stress levels could not be explained by the Singh-Mitchell equation (Singh and Mitchell, 1968). It can be concluded as well that there is no apparent threshold stress level below which creep cannot occur. A similar conclusion has been arrived at by Bishop and Lovenbury (1969).

Careful examination of Figure 6 reveals the occurrence of tertiary or accelerated creep movements at deviatoric stress of 3.7MPa (Stress level 65.9%) for sample #2 which may infer the onset of failure plane development in the sample. In that plot shown in Figure 6, the test duration should have been extended to see whether the strains will continue accelerating or will decelerate after a while. Therefore, it was necessary to conduct a creep test on sample #5 with a deviatoric stress level as high as 70% and by extending the testing time to two weeks. The axial strain and axial strain rate versus time plots for that increment are shown in Figure 8 and Figure 9 respectively.



Figure 7: Axial Strain Rate versus Time at Selected Testing Times Only for Sample DH05-07: Depth 158.70 – 159.00, $\sigma_3 = 4.3$ MPa and $\sigma_1 - \sigma_3 = 0.5$ MPa.



Figure 8: Axial Strain versus Time for Sample #5. Borehole DH05-07: Depth 158.70 – 159.00, $\sigma_3 = 4.3$ MPa and $\sigma_1 - \sigma_3 = 8.4$ MPa (~70% Stress Level).

Figure 8 and Figure 9 show that the primary creep stage was followed by a tertiary creep stage where strains accelerated marking the onset of shear plane development in the sample. However, strains started to decelerate back again to the same levels as before the tertiary stage. The deceleration of strains implies the sample is gaining strength. When the results shown in Figure 8 and Figure 9 are combined with the above conclusion that the field shear stress level is around 50% and the safety factor is approximately 2, it can be concluded that the tertiary creep response that appeared at a deviatoric stress level of 65.9% in sample #2 is transient and is followed by a stage strains deceleration where the material can sustain higher deviatoric stresses before failure.

To examine the validity of the laboratory testing program, the laboratory strain rates were compared with field strain rates resulted from in-place inclinometers installed by BC Hydro at depth 410 - 416 ft (125 - 126.8 m) in borehole DH05-07. Figure 10 shows the distribution of shear strain rates with time obtained from the results of the in-place inclinometer installed inside borehole DH05-07 at the mentioned depth.



Figure 9: Axial Strain Rate versus Time for Sample #5. Borehole DH05-07: Depth 158.70 – 159.00, σ_3 = 4.3MPa and σ_1 - σ_3 = 8.4MPa (~70% Stress Level).



Figure 10: Shear Strain Rates versus Time at Depth 125 – 126.8 m inside Borehole DH05-07.

Although the results show high noise, the general trend of the field strain rates against time was constant. The field shear strain rate ranged between 10⁻⁵ and 10⁻⁷ %/min which can be considered of the same or one order of magnitude lower than laboratory values. This comparison implies that laboratory testing for this kind of material was somewhat representative of field behaviour. Although the field results from the in-place inclinometers show the distribution of field shear strain rate with time

and the Singh-Mitchell equation describes an axial strain rate function, our comparison of laboratory axial and shear strain rate variation with time indicated that they both vary in a similar manner and are of the same order of magnitude.

The distribution of field shear strain rates versus time shown in Figure 10 is nearly constant. This may suggest that the slide plane materials are in the secondary creep phase which should be too short for geotechnical materials and may evolve into the stage of tertiary creep where the movements will accelerate rapidly until failure. However, the time period over which the measurements were taken while long is considered too short on a geological time scale and such a conclusion needs more evaluation.

8. Conclusions

The results of the study of the instability problem of the Little Chief slide could be summarized in the following points:

- The extremely slow movements of the Little Chief slide seem to be purely due to creep and are independent of any hydrological boundary conditions changes. Advanced ground water modeling is currently being carried out to investigate this notion.
- 2. The level of field shear strain rates observed was comparable to the laboratory values investigated.
- 3. The Singh-Mitchell equation (Singh and Mitchell, 1968) can be applied under high confining stresses encountered in deep seated slides.

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