ABSTRACT
Eleven large, retrogressive, multiple, translational earth slides have occurred along 10 kilometres of the Thompson River valley between the communities of Ashcroft and Spences Bridge in south-central British Columbia. Geotechnical studies have been carried out for the six most active of these earthslides since the early 1980s. The surfaces of rupture are in highly plastic clay layers of a rhythmically-bedded glaciolacustrine silt and clay unit. The reactivation movements appear to respond to drops in the level of the Thompson River after high flows, i.e. a drawdown mechanism. The groundwater system of this area and its effect on the stability of these slides is studied in this paper. We reproduced a groundwater system characteristic of one of these slides based on piezometer data collected at the site and determined the factor of safety as the groundwater system changes. The results of the groundwater system and stability modeling show good agreement with instrumentation data.

1. INTRODUCTION
The study area is located in south-central British Columbia south of the community of Ashcroft between Kamloops and Hope (Figure 1). This area has experienced eleven large, translational earthslides since the late 1800s. Six of these slides, which are in a reactivated state, have been under geotechnical investigation by both Canadian National Railway (CN) and Canadian Pacific Railway (CPR) since the 1980s.

The geology of the area were described by Ryder (1976) and Monger and McMillan (1984, 1989). Johnsen and Brennand (2004) examined the Quaternary history in more detail and Clague and Evans (2003) identified the general stratigraphy of Quaternary sediments in the Thompson River valley. Porter et al. (2002) and Keegan et al. (2003) presented some of the geotechnical investigation results on these landslides. Eshraghian et al. (2005a) showed that the Thompson River has had the main effect on the movement of these slides during their reactivation. The movement behaviour of slides and their acceleration with increased pore pressure on the rupture surfaces was studied by Eshraghian et al. (2005b).
The Thompson River may cause reactivation of these slides via a drawdown mechanism or a river bank erosion mechanism. Slide CN50.9, which is one of the six slides under geotechnical studies, is protected against river erosion by a toe berm. This paper examines the stability of Slide CN50.9 during the drawdown.

2. STRATIGRAPHY

A plan view of Slide CN50.9 with its three scarps, the CN railway, a toe berm, a section line position, and a scour hole in the Thompson River bed in front of the slide is shown in Figure 2. Figure 3 shows a cross-section of this slide based on the ground surface produced from the Light Detection and Ranging data (LiDAR), geological information, inclinometer data (Nachtigal 2001), borehole information (Nachtigal, 2001, Pritchard and Baumgard 2003), modeling the sliding stages, air photos, and site visits.

The rupture surface locations are defined based on inclinometer data and material disturbance in the boreholes (data from Nachtigal 2001). The slide is moving on two rupture surfaces: (1) a shallower rupture surface at elevation 280.9 m and (2) a deeper rupture surface at elevation 275.7 m.

3. INSTRUMENTATION

Ten boreholes were drilled at Slide CN50.9 (Figure 2) and 11 piezometers were installed in these boreholes (Figure 4). Figure 5 shows sample piezometric responses for 2001 to 2004 for piezometers installed in borehole Bh1.

Data from five inclinometers installed in boreholes Bh1, Bh3, Bh5, Bh8, and Bh9 (Figure 2) are available since April 2001 (Nachtigal 2001). The inclinometer data showed extremely slow movement on the two rupture surfaces. The movement on the deeper rupture surface was continuous and faster than the movement on the shallower rupture surface. The movement on the shallower rupture surface was not continuous and happened in July, August and September with no movement during the remainder of the year.
Figure 4. Slide CN50.9 toe cross-section A-B with borehole and piezometer locations.

Figure 5. Responses of piezometers installed in borehole Bh1 at the toe of Slide CN50.9 (see Figure 4 for borehole Bh1 location).

The deeper rupture surface displacement and movement rates, as measured by the inclinometer installed in borehole Bh1 (Figure 4), are shown in Figure 6. The rate of movement in boreholes near the toe (Bh9) is faster than boreholes farther from the toe (Bh1). The Thompson River level, measured at Slide CN50.9, and the piezometric elevation for piezometer 2 in borehole Bh1, on the deeper rupture surface, are also presented in Figure 6. This figure shows the changes of movement rates as the Thompson River level changes to a drawdown mechanism (Eshraghian et al. 2005b).

4. GROUNDWATER SYSTEM MODELING

Pauls et al. (1999) showed an example of transient groundwater modelling for their analyses of stability of a slide in the Carrot River valley, Saskatchewan, resulting from Carrot River flooding and drawdown. Similar seepage analyses were required for finding groundwater system changes due to the Thompson River fluctuations.

The main agents playing roles in the Thompson River valley groundwater system are the Thompson River level fluctuation, the perched water table in unit 8 (Figure 3), and rainfall infiltration. The Thompson River level changes more than 3 m in a normal year; however, the Thompson River fluctuation in flood years can be up to 5 m. Rainfall infiltration acts on the slope as well as on the
terrace above the slope. Channels created by the braided Thompson River between glaciation stages and later filled by fluvial gravel and sand now act as buried channels. Water, infiltrating gravel unit 8 and seeping through these buried channels, may provide a significant source of water at the crown of the Slide.

Due to the 40m depth of Slide CN50.9, rain storms in the relatively dry environment cannot provide significant changes of seepage through the slide mass. Therefore, the infiltration boundary conditions on the slide’s crown terrace and on the slope itself are assumed to be constant with time. On the other hand, considering the complex geology and stratigraphy with different hydraulic conductivities adjacent to the river, Thompson River level changes may make complex groundwater flow systems within the slide mass. The hydraulic conductivity and compressibility of the soil control the pore water pressure responses to the river level changes. Modelling this response needs a transient seepage analysis with the river bank as the transient boundary condition. We modelled the groundwater system for one cycle of the river level fluctuation from March 22, 2002, to November 17, 2002.

In the first step of the drawdown analysis, we modeled the groundwater system as a steady state model for the minimum Thompson River level of 281.6 m, which happened on March 22, 2002. Chanasyk (1986) reported 8% infiltration of annual precipitation for terraces above the slides in this area. In our model, the infiltration on the slide slope is assumed as a surface flux of 5.5% of mean annual precipitation (4.4 × 10^{-10} m/s) based on Chanasyk (1986) and considering that the infiltration to the soil on a slope is less than a horizontal terrace. Pauls et al. (1999) used a surface flux of 4.4% of mean annual precipitation (7.0 × 10^{-10} m/s). Kelly et al. (1995) used a constant surface flux of 2.0×10^{-10} m/s, 1.6% of mean annual precipitation, in their study of the Deer Creek Slide. Considering the gravel unit on the terrace above the slide (unit 8, Figure 3), the perched water table in unit 8, and the horizontal surface of the terrace, the infiltration over the terrace should be somewhat higher. Based on trials to match data from three piezometers in Bh10 (Figure 2) to the calculated pore pressure at these locations, the infiltration on the terrace was 65% of the mean annual precipitation. Through analyses of other slides in the study area, we found that the flux boundary on the slide traces depends on the area of the terrace above each slide. This may mean that most of the infiltrating water is seeping through buried channels downslope towards the terraces above the slides.

Material properties were selected based on laboratory test results reported by Eshraghian et al. (2005b) and similar materials reported in the literature. The selected values of hydraulic conductivities were adjusted during the modeling process to match the predicted heads with heads measured in the piezometers. Table 1 gives the material properties used in our modelling. Because these materials are generally laminated, the vertical hydraulic conductivity is less than the horizontal hydraulic conductivity. Considering the disturbance of this material due to the slide movement, the ratio of the vertical to horizontal hydraulic conductivity (k_v/k_h) is assumed to be 0.5. Use of k_v/k_h between 0.2 and 0.5 for landslide’s material is common practice (Pauls et al. 1999, Kelly et al. 1995). The hydraulic conductivity is assumed to be constant when pore pressures are greater than zero, but the hydraulic conductivity decreases as suction increases. Therefore, for soil units which are unsaturated at some locations, e.g. unit 6, we needed the hydraulic conductivity as a function of the suction. Figure 7 shows the hydraulic conductivity function used for glacial till (unit 6).

We used the finite element model SEEP/W\(^1\) to model the groundwater system for the steady state condition with the Thompson River level at its minimum level (282 m). The groundwater system model for the steady state stage agreed with the minimum piezometric data within the slide body.

Table 1. Material properties used in groundwater modeling.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Soil Type</th>
<th>K_{sat} (cm/sec)</th>
<th>W.C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluvial and Sand and Gravel</td>
<td>2.31\times 10^{-3}</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>U6</td>
<td>Glacial Till</td>
<td>4.63\times 10^{-4}</td>
<td>0.3</td>
</tr>
<tr>
<td>U3</td>
<td>Sandy Silty Clay</td>
<td>8.10\times 10^{-5}</td>
<td>0.42</td>
</tr>
<tr>
<td>U2</td>
<td>Clay</td>
<td>1.16\times 10^{-9}</td>
<td>0.35</td>
</tr>
<tr>
<td>U1</td>
<td>Glaciofluvial</td>
<td>1.16\times 10^{-6}</td>
<td>0.23</td>
</tr>
</tbody>
</table>

\(^1\) SEEP/W and SLOPE/W are products of Geoslope International Ltd.
state analysis, 5.5% of the annual precipitation was used as a boundary condition on the slope; however, a variable head boundary function was used for modeling the Thompson River level fluctuation between March 22, 2002 and November 17, 2002.

The same material properties and hydraulic conductivity functions used for steady state analysis were used for transient analysis (Table 1 and Figure 7). In the transient analysis, the soil storage functions were needed for soils that could become unsaturated. The soil storage function was defined based on the material data base in the SEEP/W program and the coefficient of volume change, \( m_v \), from a consolidation test. The coefficient of volume compressibility, \( m_v \), was assumed to be \( 1 \times 10^{-7} \) (m²/kN) for all units. Figure 8 shows the storage function used for glacial till, unit 6.

The transient problem was solved with 10-day time increments from March 22 to November 17. Figure 9 shows the calculated pore pressure head changes with time at the location of piezometers installed in borehole 1 (points P1, P2, and P3 in Bh1, Figure 4). Maximum changes to the Thompson River level fluctuation were noted in shallow piezometers at the toe.

The groundwater system, calculated by the SEEP/W program, shows that only a 100 metres of the slide toe, i.e. one third of the total length of slide, is actually affected by the Thompson River level changes (Figure 10). The groundwater table within the remainder of the slide stayed essentially constant. This is in agreement with small (0.8 m) changes in the piezometric elevation for piezometers installed in boreholes Bh7 and Bh10 (Figure 2 and Figure 4). Piezometric elevations of piezometer P1 in borehole Bh7 and three piezometers in borehole Bh10, showed less then one metre elevation changes during the 2001 to 2004 study period. Therefore, the Thompson River fluctuation mainly affected the blocks near the toe of the slide.

Figure 11 compares the calculated response and the measured data for piezometer P1 in borehole Bh1 (Figure 4). Although Figure 11 shows that the measured piezometric data of piezometer P1 in borehole Bh1 is more sensitive to the river level fluctuation than the calculated piezometric response for this piezometer, the general response of the model is in agreement with the data. The maximum error of 1.7 metres in the piezometric elevation calculation was considered satisfactory for engineering purposes. This comparison shows that there are smaller features that enhance the horizontal hydraulic conductivity which need to be considered in the model in order to obtain a response that is in better agreement with the measurements. The errors in the deeper piezometers and the piezometers that are farther from the toe were less than one metre.

5. STABILITY MODELING

The surface topography was reproduced from a 2 metre by 2 metre mesh of Light Detection And Ranging (LiDAR) data which has a vertical resolution of ± 0.2 metre. The locations and shapes of the two slide rupture surfaces were defined based on movement data from inclinometers installed in boreholes Bh1, Bh3, Bh5, Bh8, and Bh9 and shear disturbance in boreholes Bh6, Bh7, and Bh10 (Figures 2 and 3). Inclinometer data since April 2001 was available for boreholes Bh1, Bh3, Bh5, Bh8, and Bh9 in 1-day to 20-day reading intervals. The data demonstrate that the rupture surfaces are located within the clay-silt unit (unit 2) or at the interface between unit 2 and unit 3 or unit 6.

Because the slide is reactivated, the controlling strength parameters are residual. The residual friction angle of Slide CN50.9 rupture surfaces' material was estimated from their index properties using Stark and Eid's (1994)
Figure 10. Groundwater changes with the Thompson River level changes within Slide CN50.9.

Pore water pressure determined from transient seepage analysis by the SEEP/W program was imported into the SLOPE/W program for stability analyses. Morgenstern and Price’s (1965) method of slices was used for calculating the factor of safety every 10 days (each stage of the river level change) for blocks R-1, R-2, and R-3 (Figure 3). In each stage, the change of the river supporting force at the toe was modelled by the pressure on the river bank. Therefore, changes in the factor of safety of the blocks were caused by changing the pore pressure in the slide mass and changing the supporting load from the Thompson River. Figure 12 demonstrates the effects of river level fluctuation from March 2002 to November 2002 on the factor of safety.

The inclinometer data from borehole Bh1 at the toe (Figure 4) shows a small movement of 0.5 mm on the shallow rupture surface in block R-3 between July 2002 and November 2002. There was no movement in block 3 for the remainder of 2002. Figure 12 shows that block R-3 was marginally stable in 2002 but had a lower factor of safety between mid June 2002 and August 2002, which was the period of small movement recorded by inclinometers.

The movement on the deeper rupture surface recorded in borehole Bh1 (Figure 4) continued with different rates of movement during the study period (Figure 6). The stability

Table 2. Material property used in the slope stability analysis.

<table>
<thead>
<tr>
<th>Soil Unit</th>
<th>Unit Weight (kN/m³)</th>
<th>C' (kPa)</th>
<th>Φ' (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U6 (Till)</td>
<td>18</td>
<td>0</td>
<td>26</td>
</tr>
<tr>
<td>U3 (Sand and silt)</td>
<td>19</td>
<td>0</td>
<td>22</td>
</tr>
<tr>
<td>U2 (Clay-Silt)</td>
<td>19</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>Fluvial</td>
<td>18</td>
<td>0</td>
<td>24</td>
</tr>
<tr>
<td>Berm</td>
<td>18</td>
<td>0</td>
<td>30</td>
</tr>
</tbody>
</table>
analysis result (Figure 12) shows that while block R-2 was always unstable, block R-1 was stable. Both of these blocks are moving on the deeper rupture surface. While block R-2 contains almost half of the slide mass at the toe, block R-1 contains all the slide mass. Therefore, only half of the slide near the toe on the deeper rupture surface was unstable during the 2002 study period. This conclusion is supported by the fact that no movements or new crack development was recorded at the borehole Bh10 location (Figure 2).

In 1997, an extension to the toe berm was constructed for Slide CN50.9 to improve the stability of the slide. The average width of the berm was assumed to be 4 metres. Transient seepage analyses and stability analyses were repeated for the cross-section with and without this new berm to investigate its effect on stability. This toe berm most affected block R-3. The construction of the toe berm caused a 3% improvement in the factor of safety of block R-3, a 1% improvement in the factor of safety of block R-2, and a 0.2% improvement in the factor of safety of block R-1. Therefore, the factor of safety of block R-2 was still below 1. Figure 13 shows the factor of safety of block R-3 before and after the berm extension was built. The berm may not have been sufficient to halt the movement on the deeper rupture surface within block R-2, but probably reduced the rate of movement of block R-3 at the toe.

Factors of safety for the blocks changed with river level changes. During the study period in 2002, the difference between the minimum and maximum factor of safety for block R-1 was 2%, the difference between maximum and minimum factor of safety for block R-2 was 3%, and the difference between maximum and minimum factor of safety for block R-3 was 15% (Table 3). This demonstrates that the river’s effect on the stability of the blocks diminished with distance from the slide toe.

Although the general results of the stability analyses agreed with the field observations, still there are uncertainties. Main sources of uncertainties in calculated factor of safety are uncertainty in the material properties and the pore pressure on the rupture surfaces. A sensitivity analysis showed that one degree increase in residual friction angle of clay-silt unit (unit 2) and two degree increase in the residual friction angle of the rest of materials in Table 2 improved the factor of safety of block R-2 by 9%. This new material properties resulted in minimum factor of safety of 0.96 for block R-2 (rather than 0.87 in Table 3).

The deeper blocks and shallower block differ in the effect of river level fluctuations on their stability. The factor of safety of the shallower block, block R-3, decreases in response to increases in the Thompson River level (Figure 12). The minimum factor of safety for block R-3 occurs three weeks after the maximum river level is reached. On the other hand, the factor of safety of the deeper blocks, block R-2 and block R-1, increases with the Thompson River level rising. The maximum factor of safety for blocks R-1 and R-2 occur a few days after the

| Table 3. Change of Factor of Safety for different blocks in Slide CN50.9 during the study period in 2002. |
| --- | --- | --- | --- |
| Block | Minimum F.S. | Maximum F.S. | Change in F.S. (%) |
| R-1 | 1.25 | 1.27 | 2 |
| R-2 | 0.87 | 0.90 | 3 |
| R-3 | 1.06 | 1.21 | 15 |

Figure 12. Change of factor of safety with the Thompson River level fluctuation.

Figure 13. Effect of the toe berm extension on stability of the toe block, block R-3, in Slide CN50.9.
maximum Thompson River level and then decreases as drawdown occurs. This is almost opposite behaviour to the factor of safety changes for block R-3. Increases in pore pressure from rising water levels were greater for the shallower block than for the deeper blocks. Therefore, the supporting effect of the river plays a main role in changing the stability of deeper blocks. Whenever the river level is increasing, the stability of the deeper blocks is improved by the river supporting effect and vice versa.

6. CONCLUSIONS

Field measurements at Slide CN50.9 indicate that movement on the deeper rupture surface accelerates during the Thompson River drawdown period. The groundwater modeling and stability modeling supports this fact. While the berm built at the slide toe has contributed to the stability of the shallower toe block and has protected the slide toe against river erosion, it has not prevented movement on the deeper rupture surface.

Stability modeling demonstrates that the deep and larger block (block R-1) was stable, but that the deep smaller block (block R-2) was unstable. This means that the toe portion of the slide is moving on the deeper rupture surface, but this movement does not extend to the head on the deeper rupture surface. As predicted by the modeling results, no new cracks have developed at the head. However, additional inclinometer data at the head are needed for confirmation.

The effect of river fluctuation on the shallower block (block R-3) is mainly due to increasing pore water pressure on the shallower rupture surface. The higher hydraulic conductivity of material at the toe increases the pore pressure response on the shallower rupture surface to the river level fluctuation. On the other hand, the pore water pressure on the deeper rupture surface does not change with the river level fluctuation as much as shallower rupture surface pore water pressure. Therefore, the change of the stability of the deeper blocks with the river level fluctuations occurs mostly because of the supporting effect of the river on these blocks.

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