Re-examination of the Little Smoky Slide

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ABSTRACT
Movements of the Little Smoky valley slopes have been measured since the late 1950s. The movements have had an adverse effect on the serviceability of the Little Smoky Bridge carrying Highway 49 in north-western Alberta. Previous investigations included a field instrumentation program in addition to limit equilibrium analyses. The results showed that the slide is retrogressive and a movement trigger is toe erosion. Based on movement records from the 1960s, we have carried out transient seepage analyses to investigate the possible effects of river level fluctuations on movement rates. The preliminary results showed acceptable correlations. Continuous monitoring with recently installed piezometers and slope indicators is being undertaken to validate those correlations. The recent monitoring proved valuable though in filtering out the creep component of the total movement. It is believed that the grading operations that accompanied road construction in the fifties have triggered movements.

RÉSUMÉ
Mouvements du pente sud de la vallée Little Smoky ont été mesurées pendant cinquante années. Les mouvements ont eu un effet négatif sur l'état de fonctionnement du Pont Little Smoky de l'autoroute 49 au nord-ouest de l'Alberta. Enquêtes précédentes comprenaient un programme d'instrumentation de terrain, en plus des analyses d'équilibre. Les résultats ont montré que le glissement est regressive. Les mouvements ont déclenché en suivant l'érosion fluvial du front. Sur la base de dossiers de mouvement à partir des années 1960, nous avons procédés à des analyses d'infiltration transitoire pour enquêter sur les éventuels effets des fluctuations du niveau de la rivière sur les mouvement. Les résultats préliminaires ont montré des corrélations acceptables. Une surveillance en continu avec récemment installé des piézomètres et des indicateurs est en cours afin de valider ces corrélations. La récente suivi avérée si précieuse dans le filtrage de la composante de fluage de la mouvement totale. On croit que les opérations qui ont accompagné la construction de la route dans les années cinquante ont réactivé des mouvements.

1. Introduction

The Little Smoky Slide lies on the south and the north banks of the Little Smoky River 48 km north of Valleyview in north-western Alberta (Figure 1). The bridge carrying Highway 49 across the north flowing river was completed in 1957. Movements of the south abutment and pier were noticed soon afterwards and have continued. The river valley at this location is about 90m deep and has an average slope of 7 degrees. The steel truss bridge is 271m long. The deck is supported by three abutments and four pier foundations. The bottom level of the bridge deck is approximately at elevation 496m and the minimum river level is approximately at elevation 487.5 (Hayley 1968, Thomson and Hayley 1975, Alberta Infrastructure 1998 and Skirrow et al. 2005). Downstream and west of the bridge, downslope movement rates were about 100 mm/yr in the sixties and still persist. The movement records for both the south and north slopes are available since 2001. The southeast and north slopes move at rates of 30 and up to 70 mm/yr respectively. Hayley (1968) and Thomson and Hayley (1975) revealed toe erosion as a main trigger of movement. Since 2001 extensive instrumentation that includes both south and north slopes has been employed in order to arrive at a complete picture of the movement pattern.

This paper presents a description of the site geology, a review of the previous studies and the results of the current re-examination of the slide in order to explore other possible mechanisms of movement and filter out the effect of toe erosion from other possible triggers.

2. Site Geology

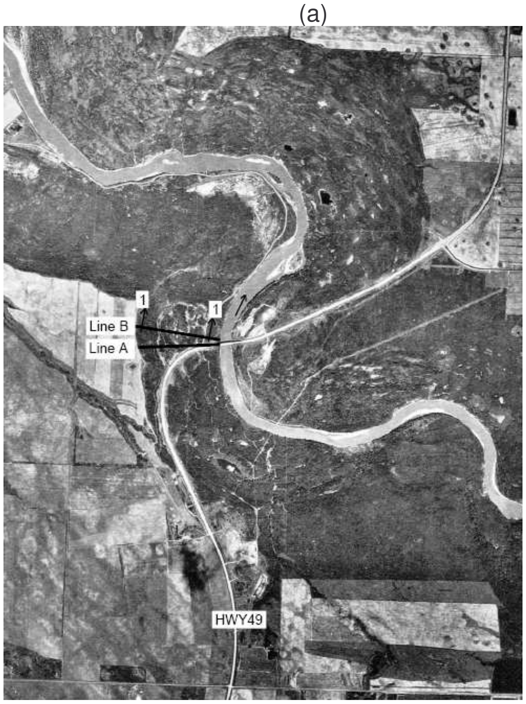
The Little Smoky River at the bridge is flowing in a valley cut into flat lying sandstones and shales of Upper Cretaceous age during the Tertiary period. The thalweg of this wide, gently sloping valley is eroded into the Puskwaskau Formation, soft grey fissile marine shales, part of the Smoky Group (Hamilton et al. 1999).

Liverman et al. (1989) showed that the surface till in the Grande Prairie region on west central Alberta is Late Wisconsin in age and represents the only Laurentide glaciation in this area of Alberta. As Cruden et al. (1993) pointed out; the Late Wisconsin Laurentide ice sheet blocked the regional drainage while advancing up the regional gradient of the area. Hence preglacial lakes have been formed in the broad preglacial valleys. The clay till reflects the composition of the poorly indurated Smoky Group shales over which the ice advanced. After ice retreat, the melt water incised through the Pleistocene deposits to form the current valley systems around the Peace, Smoky, and Little Smoky rivers.

Figure 1: The Little Smoky Slide Location. (a) Alberta Map showing the site, (b) Air Photo taken in 1967 showing the

slide terrain (Reproduced with Permission from Alberta Sustainable Resources Development, Air Photo Distribution).

(a)



(b)

The river bed essentially consists of coarse boulders (Hayley 1968). The rivers in the early Pleistocene carried gravels and some were deposited on the river terraces. These preglacial Saskatchewan sands and gravels had their origin in the foothills of the Rocky Mountains. They contained quartzites, cherts and sandstones. Other boulders in the river channel were eroded from the till. They are located in some locations between bedrock and the overlying Till (Rennie 1966).

3. Previous and Current Investigations

Hayley (1968) focused on two adjacent sections (line A and line B in Figure 1) normal to an outside meander of the Little Smoky River 60m downstream of the bridge. The field program involved installation of surface monuments in addition to ten slope indicators along two lines that extended from the river to the prairie level beyond the slide scarp. Two piezometers were installed to determine ground water conditions at the site. Borehole drilling at the site revealed the stratigraphy at the Little Smoky site to be composed of till overlying shales. The upper layer of the shale was soft and fractured, below it became generally hard and intact. The percentage of sand, silt and clay particles in the till ranged between 23-60%, 31-40% and 9-35% respectively. The upper soft shale was composed of 51-57% of silt, 38-43% of clay and 5-6% of sand. The index properties of the till and shale units are listed in Table 1. Triaxial and direct shear tests were carried out on shale samples to determine peak and residual strengths. Peak friction angle was found to be 32^0 and residual angle was equal to 14^0.

In addition to the work done by Hayley (1968), Alberta Infrastructure and Transportation recorded monthly the movement of the bridge pier and abutment during the late sixties. Since 2001, semi-annual movement records have become available when Alberta Infrastructure and Transportation in collaboration with Thurber Engineering Ltd. started an extensive monitoring program of the site in order to assess the overall movement regime and plan for future mitigation strategies (Skirrow et al. 2005 and Proudfoot and Tweedie 2002).

The data from slope indicators together with surface surveying showed the slide to be retrogressive. Hayley concluded that toe erosion is the main trigger of movement. This mechanism of movement was verified by Limit Equilibrium Analyses (LEA) assuming the friction angle along the main movement surface was residual. Figure 2 shows the stratigraphy as well as the geometry of the moving blocks as interpreted by Thomson and Hayley (1975). The inclinometers installed in 2001 sheared off by the end of 2005. Accordingly, three boreholes were drilled in 2007 and inclinometer casings as well as nine vibrating wire piezometers were installed in the southeast, north and southwest slopes.

Table 1: Summary of Index Tests Results (Modified after Thomson and Hayley, 1975)

Property	Till	Shale	
		Soft	Hard
Natural Water Content (%)	21-22	21	15
Liquid Limit (%)	43-48	55	48
Plastic Limit (%)	18-21	31	23
Plasticity Index I_p (%)	22-30	24	25
Bulk Density (kN/m^3)	19.50	21.78	-

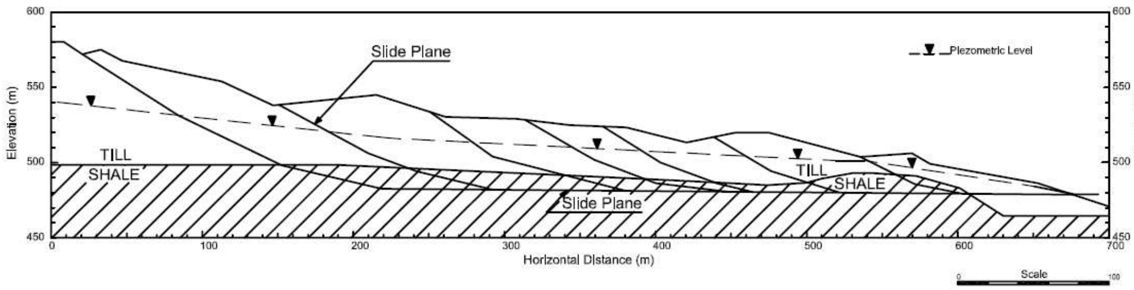


Figure 2: Cross Section 1-1 along Line B as indicated in Figure 1 (Modified after Thomson and Hayley, 1975)

4. Effect of River Level Fluctuation on Movement Rate

In addition to toe erosion, the effect of changes in boundary conditions due to river level fluctuations and/or precipitation has to be investigated. The effect of river level fluctuations over the years on the pore pressure inside the slope has been investigated using the SEEP/W Finite Element code (Krahn 2004). A continuous record of the south pier movement was available on a monthly basis during the period from May 29th 1965 to December 1st 1968. The south pier is located approximately at 45m from the toe of the slope. Figure 3 shows a plot of each of pier movement and river level against time.

Due to the lack of any field tests to measure the in-situ hydraulic conductivity and because laboratory tests are not reliable in such case due to weathering of the upper soft shale, it was important to revert to similar case histories especially from Dams construction projects founded on similar soil properties (See Table 2). The entry values for saturated hydraulic conductivity were: $K_{sat\text{-}shale} = 2.50 \times 10^{-07}$ m/sec, and $K_{sat\text{-}till} = 3.00 \times 10^{-10}$ m/sec.

The very low hydraulic conductivity of the till is confirmed by our visual inspection of the recently drilled cores in 2007. The inspection showed that the upper layer of the till contains high clay content and shows no signs of fracturing or disturbance. The same cross section shown in Figure 2 was used in the seepage analysis. The available river level records for the years 1965 – 1968 were idealized to be used as an input to the transient SEEP/W analysis. The analysis results are viewed as the resulting pore pressure at the pier location at the elevation of the slide plane. The period of constant water level was considered as a steady state condition and was used as an input for the subsequent transient analysis. The peak water level recorded on April 29th, 1965 was one of the two highest values over the last 50 years. The delayed effect of this peak alone on pore pressure was studied and the results are shown in Figure 4. The instantaneous pore pressure head response during the time of the maximum increase in water level was only 6% of the water level difference. By November 17th of the same year, the pore pressure head response became more than 95% of the maximum water level difference. Provided the highest peaks in river level occur usually in spring, the river level fluctuations effect is not extended to the next year. Therefore, transient analyses could be conducted on each year separately and not for the whole period (1965 – 1968) in a single analysis.

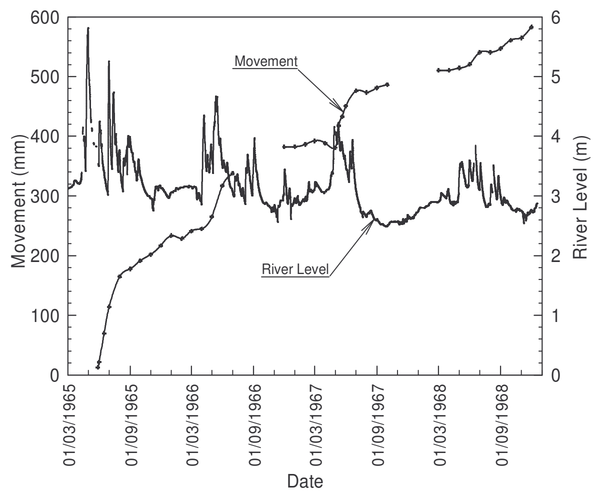


Figure 3: Pier Movement and River Level against Time (Source: Government of the Province of Alberta, Department of Highway Records (1968) and Environment Canada)

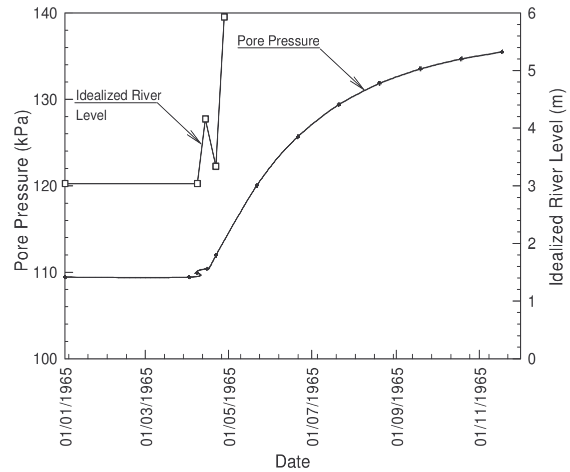


Figure 4: Pore Pressure Response to Peak Water Level on April 29th 1965

Table 2: Hydraulic Conductivity Values for Till and Shale from Similar Stratigraphies

Case History	Summary of Foundation Material	Estimated Values	Comments
Previous Detailed Studies on Little Smoky Slide by Rennie (1966)	Same as detailed above	$K_{Till} = 3.00 \times 10^{-10}$ m/sec	Although Rennie relied on laboratory undisturbed samples, he stated that he "*could find no evidence of fissures, joints or cracks in the specimens obtained*"
Paddle River Reservoir Area near Mayerthorpe, Alberta (Pretula and Ko, 1982)	Glacio-lacustrine deposits, underlain by brown and grey tills; overlying fractured sandstones and shales of the Wapiti, Whitemud and Battle formations of the Upper Cretaceous age.	$K_{Till} = 1.00 \times 10^{-10}$ m/sec $K_{Shale} = 4.20 \times 10^{-07}$ to 7.00×10^{-06} m/sec	
South Saskatchewan River Dam Site (Morton, 1964)	Jointed and fissured Shales of the Upper Cretaceous age.	$K_{Shale} = 5.07 \times 10^{-07}$ m/sec	
Site C near Fort St. John, BC. (Cornish and Moore, 1985)	Moderately weak, flaky to fissile, silty shale of the shaftsbury formation of the mid cretaceous age.	$K_{Shale} = 1.00 \times 10^{-07}$ m/sec	Using In-situ Packer tests.

The results of the transient SEEP/W analysis are illustrated in Figure 5. It is clear that there is a correlation between the rate of movement and pore pressure response at the location of the pier at the slide plane elevation. The results have been plotted as pore pressure versus movement rate in Figure 5. Although the relation appears to be scattered as a first impression, careful examination shows that there is a possible coupling effect on movement of pore pressure fluctuations and toe erosion that takes place at high pore pressure values (high water level and obviously high water flow). The points enclosed in the ellipse, for example, represent the pore pressure response during spring and summer of 1965 (exceptionally high water level and flow). A proposed mathematical representation of this coupled effect is shown on the same figure. The results of the currently undergoing field program will help to validate the above correlation.

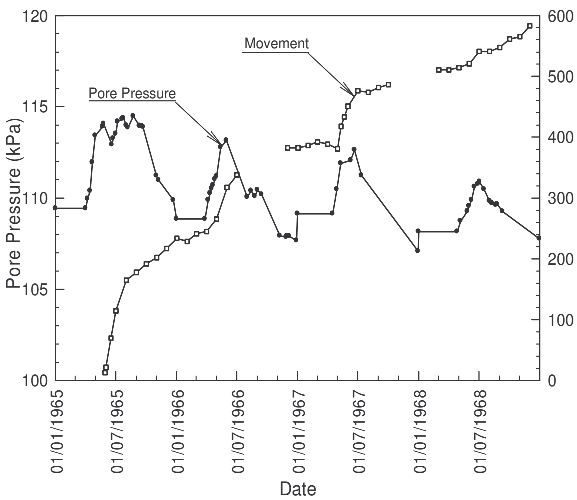


Figure 5: Calculated Pore Pressure and Pier Movement versus Time

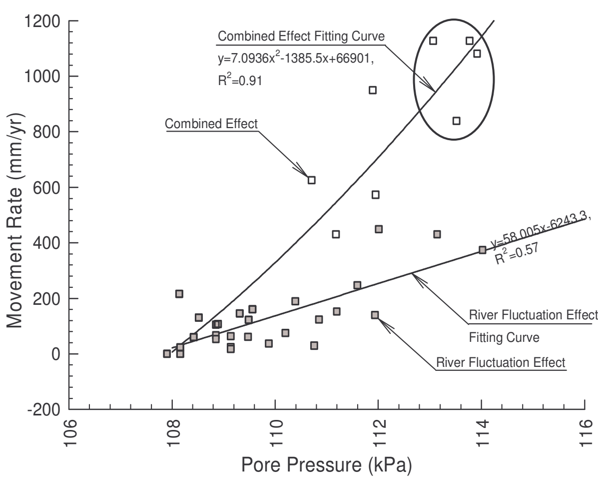


Figure 6: Proposed Mathematical Representation for Causes of Movement

It was, however, possible to find some useful correlations that may prove valuable in verifying the above hypothesis. The pier movement record had started in May 29th 1965. The amount of yearly movement between the 29th of May, 1965 and the corresponding date in 1966, 1967 and 1968 was easily calculated, and plotted against the cumulative river level and the cumulative river flow. Figure 7 and Figure 8 show these correlations.

The correlations are obviously strong. The recent monitoring by Thurber Engineering (2001 – 2004) showed similar correlations as well. Figure 9 is a plot of total yearly movement against cumulative river water level between 2001 and 2004. Cumulative river flow effects on yearly movements show a similar trend.

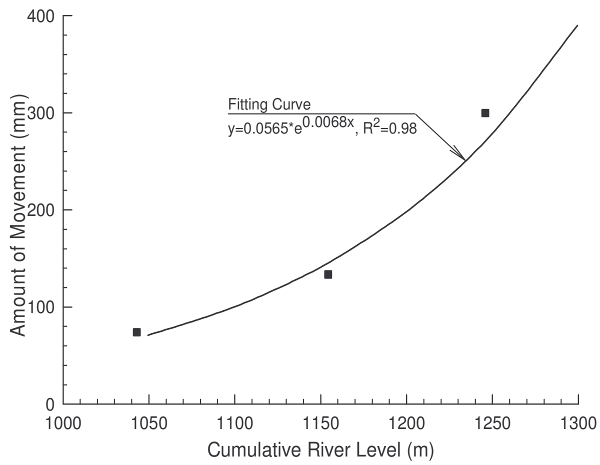


Figure 7: Total Amount of Yearly Movement of Pier between May 1965 and December 1968 against Cumulative River Level in a year

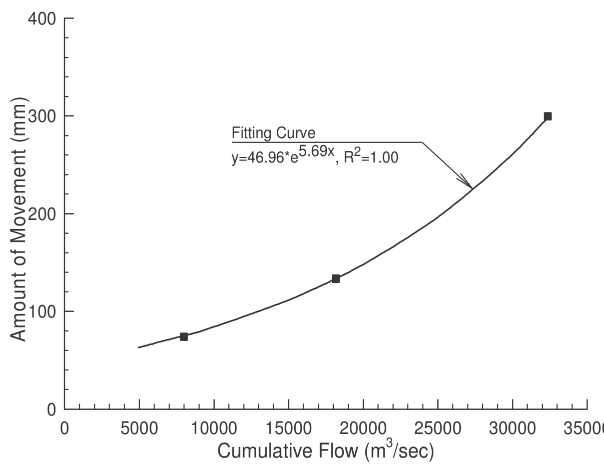


Figure 8: Total Amount of Yearly Movement of Pier between May 1965 and December 1968 against Cumulative River Flow in a year (Pier Records 1965 – 1968)

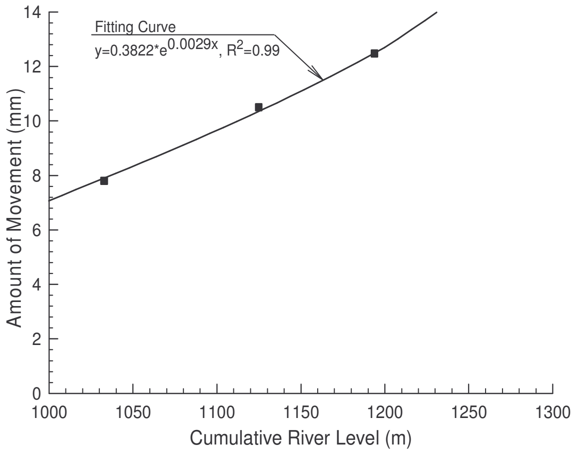


Figure 9: Total Amount of Yearly Movement against Cumulative River Level in a year at Slope Indicator SI01-9 South of Bridge (2001 – 2004)

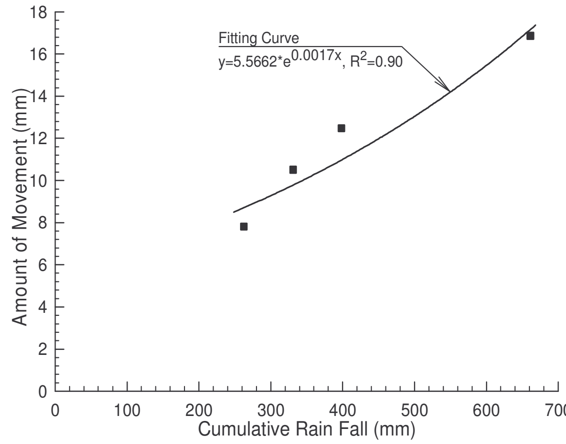


Figure 11: Amount of yearly Movement against Cumulative Rain Fall at Slope Indicator SI01-9 South of Bridge (2001 – 2004).

5. Rainfall Effect

As the river level fluctuations' effect on the movement rate was addressed, it was necessary then to explore the possible effect of rain fall. The amount of yearly movement was plotted against the cumulative rain fall during the sixties and from 2001 to 2004. Figure 10 and Figure 11 show these plots. The correlations were either weak or very poor and can not be relied upon. In addition, our visual inspection of the recently drilled borehole at the southwest slope indicated that the top layer has high clay content and does not show any signs of jointing or fissuring. This observation has been reported as well by Rennie (1966) (See Table 2). After continuous site visits for reconnaissance and monitoring, it was clearly noticed that some drainage measures are located in both the north and south slopes. This helped with draining surface water resulting from precipitation. It can be concluded then that river level fluctuations and river flow has a more dominating effect on movement than rainfall.

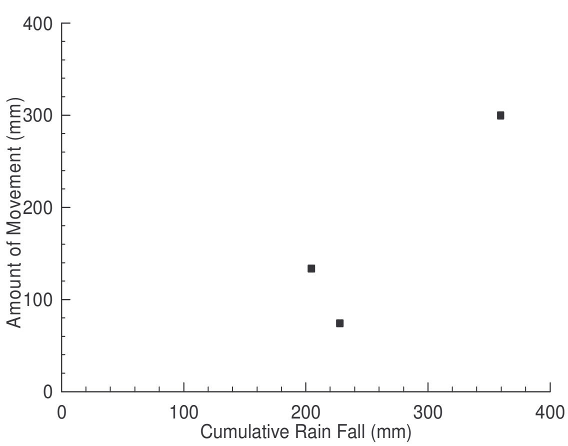


Figure 10: Amount of yearly Pier Movement against Cumulative Rain Fall (Pier Records 1965 – 1968)

6. Creep Component of Movement

The most recent site monitoring started in April 2007 with the aim of getting a more detailed picture of the movement regime than the previous interpretation that relied on semi-annual readings. The results available from the south slope site that are shown in Figure 12 indicate that movement persists during the late fall and winter. The effect of both river erosion and pore pressure changes is minimal during that time of the year. Hence it is considered that the viscous properties of the materials forming the rupture surface are responsible for the continued movements during the late fall and winter. The results shown in Figure 12 indicate that the shales at the Little Smoky site may creep at a rate of 15mm/yr. This would account for up to half the total movement that occurs on the south side. Martin et al. (2001) reported a movement rate of 20mm/year in clay shales in a reservoir slope upstream of the Oldman River dam in south western Alberta. The recorded rate represented the residual movement after filling the reservoir to the operating pool level. However, they attributed this movement to swelling associated with reservoir infiltration along the open joints parallel to the valley wall and not to pure creep effects. Based on the distance between inclinometers and recorded displacements, Martin et al. (2001) expressed the horizontal strains as percentage per log cycle of time and found that they ranged from 0 to 0.3%. Other researchers reported swelling strains in clay shales ranging between 0.2 and up to 3% (Lo and N., 1990; Lo et al., 1978; Cornish and Moore, 1985; and Phelps and Brandt, 1989).

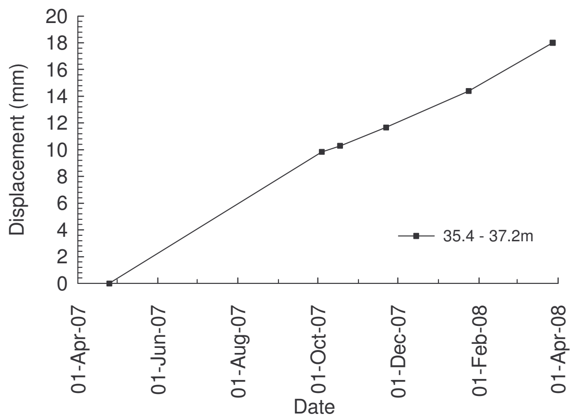


Figure 12: Displacement versus Time within the Movement Zone for the Slope Indicator Installed at South Slope

Eshraghian et al. (2007) reported sixty cases from the literature for reactivated translational earth slides. They found that rainfall, toe cuts and river erosion are the likely triggers for 92% of the studied cases. There wasn't any account for the contribution of creep to the total movement. Picarelli and Russo (2004) had the same observation for some reactivated slides triggered by pore pressure changes along the rupture surface. This is mainly because the continuous variations in boundary conditions unavoidably obscure the time dependent effects (Picarelli and Russo, 2004).

7. Conclusions

Based on the results obtained by numerical analysis and field monitoring, the very slow movements at the Little Smoky slide are reactivated by all or some of the following triggers:

1- River erosion which seems to be the main contributor to movement especially in the area studied previously by Hayley in 1968 and in the north slope,
2- Pore pressure changes due to river level fluctuations, and
3- Creep or viscous deformation.

The field monitoring will be completed by the end of September, 2008. By this date a complete picture of the movement trend should be available. Moreover, the contribution of each trigger could then be quantified. This will prove valuable in deciding upon the proper mitigation option.

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