MECHANISMS AND KINEMATICS OF RIVER VALLEY LANDSLIDES IN EDMONTON

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ABSTRACT

A study of three translational landslides along the North Saskatchewan River Valley in Edmonton is presented in this paper. The major focus is on kinematics and mechanisms of deep seated landslides in bedrock of the Upper Cretaceous Horseshoe Canyon Formation. The study found that the river valley landslides are caused by a combination of several factors, including toe erosion by the river, the effects of residential development behind the slope crests including the rise of groundwater levels, and softening of the bedrock materials at the valley wall. The landslides developed in stages starting as a minor toe failure and gradually retrogressing upslope. Development of landslide stages observed in the North Saskatchewan River Valley can be described as follows;

- Pre-failure slope movement can be characterized by minor failures at the toe and the mid-slope area.
- Major slope failure can range from several days to several years. The rate of movements depends on type and thickness of the overburden materials and the bedrock above the surface of rupture.
- During the major slope failure, the main body translates along the surface of rupture and a distinct graben feature appears at the head of the displaced material due to subsidence.
- After a major failure, displaced material rests on the rupture surface and the factor of safety improve with the new slope configuration. During this period, some changes in the external condition such as increase in groundwater level, changes in slope configuration and loading at the slope crest can reduce the factor of safety to below unity.

1 INTRODUCTION

Landslides are downward and outward movements of slope-forming materials composed of natural rock, soils, artificial fills, or combinations of these materials (Varnes 1958). Landslide can occur in a wide range of environments and ground conditions. Landslides may be caused by external disturbances such as undercutting of the toe or an excavation without support. On the other hand, landslides may occur on slopes that have been stable for many years.

In Edmonton, the North Saskatchewan River and its several tributaries have cut their present valleys post-glacially. The valley slopes are often steep with changes in profile resulting from changes in geological formation. The valley slopes are marginally stable (Thomson 1970) and large scale, rapid landslides and slow progressive slope movements often affect residential developments and the city's infrastructure along the river valley.

Most of the river valley landslides in Edmonton have occurred on valley slopes that had been stable for many years. The mechanisms of these slides are complex and there has been no detailed investigation of the failure mechanisms of these slides. Stability analyses of river valley landslides are challenging due to complex kinematics involved. Therefore, a study of the landslide mechanisms and kinematics of these slides is necessary. This paper presents case studies of three translational landslides along the North Saskatchewan River Valley in Edmonton. The major focus is on the evolution of the landslides, including the development of stages and the kinematics of landslides in weak rocks. The landslide terminology used in this paper follows Cruden and Varnes (1996).

2 KEILLOR ROAD LANDSLIDE

The Keillor Road Landslide occurred in the fall of 2002 on the outside bend of the North Saskatchewan River, where Keillor Road traverses down from a flat upland area to a low level terrace (Figure 1). Due to the failure, a 5 m deep graben appeared at the head of the displaced material and the toe of the slope moved 22 m into the river. The total volume of soil and rock involved in the landslide was in the order of 100,000 m^3. After the 2002 failure, continued slope movements caused further downward movement of the graben over a period of 2 years, resulting in a further 3 m retrogression of the main scarp. Movement of displaced materials continues to be observed up to the present day.

2.1 Landslide history

The Keillor Road Landslide started as a minor toe failure in 1989 causing some damage to a recreation trail at the toe of the slope (Barlow 1989). Fill had previously been placed to remediate a drop at the edge of the trail. After failure, a concrete retaining wall was constructed at the downslope edge of the trail to locally protect the trail from the effects of further instability (Figure 2).

In 1994, the movement progressed upslope causing some damage to Keillor Road, located about 40 m above the toe (Bergman and Ruban 1995). The area, located on the outside of a horizontal curve near the top of Keillor Road, had been repaired periodically by the City of Edmonton. In 1997, an 8 to 15 m deep cast-in-place tangent pile retaining wall was constructed to protect the roadway.

The wall performed satisfactorily until August 2001 when a crack was observed across the roadway and the concrete wall. With time, the crack developed into a vertical scarp and a major failure occurred in the fall of 2002. The scarp was 50 m wide at the crown but widened to nearly 200 m at the river level. When the failure occurred, the head of the displaced material moved downward forming a graben. The main body of the slide translated along a horizontal plane in the bedrock.

2.2 Stratigraphy

A stratigraphic profile of behind the valley wall can be described as follows.

- The bedrock, the Horseshoe Canyon Formation of the Edmonton Group, comprises interbedded layers of clay shale, bentonitic sandstone, sandstone, coals, and bentonite seams. Bedrock samples revealed that the clay shale was often brecciated with slickensides.
- The bedrock is overlain by a 2 to 6 m thick till deposit. The till is stiff to very stiff and high plasticity, with numerous local bedrock fragments and a few carbonate fragments.
- The till is overlain by a layer of lacustrine clay. The lacustrine clay is 4 to 7 m thick, silty, firm to stiff, and has low to intermediate plasticity.

2.3 Post-failure Slope Movement

After the major failure in 2002, a field observation program was carried out to monitor the post-failure slope movement. Landslide features such as the graben, tension cracks, scarps, and ridges were mapped monthly in the spring and the summer of 2003 and 2004 (Figure 3). A total station survey was conducted in the spring of 2003 and 2004 to monitor movements of the upper pile wall and to provide a cross sectional survey of the landslide topography (SoeMoe et al. 2005).

In the fall of 2002, 18 crack meters (CM) were installed in the displaced material to monitor the surface expression of the slope movements (Figure 3). Vertical and horizontal movements of the CM were monitored regularly in the spring and summer of 2003 and 2004. As the landslide progressed, significant slope movements occurred and middle part of the main body slid into the river in July 2004. The maximum movement of the counter scarp was 3 m toward the river from May of 2003 to May of 2004. Minor scarps which formed at the lower portion of the displaced material, were attributed to retrogressive failure.

The horizontal movements of CM are presented in Figure 4. CM-13 was located in the initial toe of the slide and slid down to the river after a period of heavy rainfall in July 2004.

CM-16, located at the toe of the slide, was damaged by the slide in early June of 2004. Maximum movements were observed at the centre of the slide. As shown in Figure 15, the recorded crack displacements increased significantly after periods of heavy rainfall.

Part of the upper pile wall was located inside the graben and settled together with the displaced material. The coordinates of the top of the pile wall were surveyed in May 2003 and May 2004 (Figure 5). The maximum recorded horizontal and vertical movements were 2.3 m and 5 m, respectively, in 2003 and an additional 1.7 m and 2.3 m of movement were measured, respectively, in 2004.

2.4 Observed landslide stages

Movements observed at the Keillor Road Landslide revealed the development of landslide stages with time. At Keillor road, initial movements started as a toe failure in 1989 and a major failure occurred in the fall of 2002. Inclinometers installed prior to the major failure revealed the development of the main scarp. A comparison of the pre-failure cross-section and the post-failure surveyed cross section conducted in 2003 and 2004, and the pile settlement, are shown in Figure 6. As shown, the failure mechanism extended below the pile wall. Downward movement of the material inside the graben and the translational movement of the main body can be seen in Figures 6b and 6c. As the landslide progressed, more cracks appeared in the main body as a result of slope deformation. The upper pile wall at Keillor Road moved downward, and piles at the trail near the toe tilted forward as the displaced material pushed the piles toward the river.

3 WHITEMUD ROAD LANDSLIDE

On the morning of October 23, 1999, a large landslide occurred along a 270 m section of the North Saskatchewan River Valley in Edmonton (Barlow and Froese 2000). The failure affected seven residential lots on the west side of Whitemud Road between the intersection of Ramsay Road and 43rd Avenue (Figure 7). The upper two-thirds of the valley slope slid along a rupture surface located in the bedrock. As the failure progressed, the soil and rock above the failure plane cascaded over the bedrock and slid into the river. The total volume of soil and bedrock involved in the landslide was in the order of 250,000 m^3. After the initial failure, 50,000 m^3 of this material was displaced into the river channel at the toe of the slope. As the main body translated along the surface of rupture, subsidence occurred at the head of the displaced material, resulting in a vertical drop of up to 18 m.

3.1 Landslide history

Prior to the major landslide in 1999, several movements had occurred downstream of the 1999 landslide location (Figure 8). In 1967, a failure occurred 300 m downstream of the 1999 landslide location. But the failure did not affect the residential properties behind the valley wall. In 1976, a second failure occurred north of the 1967 failure involving the overlying glacial deposits and the bedrock. Significant observations before the 1999 landslide are listed below.

- No significant slope movements were observed prior to 1997.
- The movements of the lower portion of the slide commenced at some point in 1997 or 1998. The evidence was a block of soil and trees tumbling down to the river edge. Ground cracking was observed in a trail located in the middle of the slope.
- Minor cracking in the cement work in Lots 6 and 7 was noticed by the summer of 1998.
- By the summer of 1999, the translational movements in the lower slope had progressed and formed a scarp at mid slope.

3.2 Residential lot development

The lots along the valley crest on Whitemud Road (Lots 5 to 14) were developed over a 20-year period from 1967 to 1988. Significant lot grading was required to reduce the grade on Lots 9 through 13 and to bring up the grade between Lots 6 and 8. The largest portion of fill was used to fill in a kettle hole located on Lot 7(Barlow and Froese 2000).

3.3 Stratigraphic profile

Post failure borings (Barlow 2005; Barlow and Froese 2000) revealed that the bedrock comprises interbedded layers of mudstone, clay shale and sandstone with thin bentonite layers (Figures 9). The bedrock is Upper Cretaceous in age and part of the Horseshoe Canyon Formation of the Edmonton Group (Bayrock and Hughes 1962). When exposed to weathering processes, the bedrock swells and softens, particularly in areas of seepage discharge. The sandstone varies from a low plastic sandy clay to a weakly cemented soft rock. The mudstone and clay shale are generally hard, massive, high plastic and without any distinct fissility. Three separate bentonite layers with a varying thickness from 50 to 400 mm were identified from deep borings (Figure 9).

The bedrock is overlain by an 8 to 10 m thick till deposit. The till deposit is characterized by a clay matrix with numerous local bedrock fragments and a few carbonate fragments, mostly of the sand fraction.

Overlying the till is a 30 to 35 m thick kame deposit of sand, typically formed by meltwater channels under the retreating ice sheet (Godfrey 1993). The sand is generally in a dense to very dense state with the moisture contents less than 10 %. The kame sands are overlain by a layer of lacustrine clay. The lacustrine clay is less than 6 m thick, silty, and soft to stiff, with a low to intermediate plasticity. Fill material of 3 to 5 m thickness was identified within Lots 5 to 7, directly overlying the sand deposit.

3.4 Post-failure movement

Major movements in the Whitemud Road landslide occurred within one day (Barlow and Froese 2000). A distinct graben feature formed at the head of the displaced material as the main body translated along a weak plane in the bedrock. Figure 10 presents pre-failure and post-failure cross-sections of the slide area and identifies soil and rock layers deduced from the drilling information (SoeMoe et al. 2006). As shown in the figure, the failure geometry of the Whitemud Road slide comprises a steeply dipping main scarp and a surface of rupture seated in the bedrock. Boreholes advanced inside the displaced material revealed two different profiles. The borings inside the graben encountered mostly sand, indicating most of the materials inside the graben are from the overlying sand deposit. Boreholes drilled outside of the graben boundary revealed an almost undisturbed stratigraphic profile of sand and till overlying bedrock, indicating that these materials translated along a weak plane.

3.5 Long term slope movement

Continued movement of displaced materials was recorded after the major failure in 1999. These movements were typically related to seasonal variation of the groundwater level and construction activity of the valley wall. Although inclinometers installed behind the valley wall showed movements of less than 10 mm from 1999 to 2004, significant slope movements were observed from the inclinometers installed inside the displaced material. The rate of movement of displaced material increased from 1.5 mm/month in 2000 to 3.6 mm/month in 2001 and 7.0 mm/month in 2002. The greater magnitude of slope movements in 2002 was partly attributable to remedial construction activities which involved the installation of horizontal drains. The maximum movement was located at the centre of the displaced material.

4 FOREST HEIGHTS PARK

Forest Heights Park is located on the eastern bank of the North Saskatchewan River, immediately south of the Dawson Bridge near downtown Edmonton. The valley wall around this area is known for active slope movements since the early 1900s, when coal mining was conducted in the area. As Edmonton expanded, this area was designated as a recreational park with public access roads and recreational trails (Figure 11). In the early 1980's, a toe berm was constructed as part of bank stabilization and protection works, to prevent or minimize toe erosion by the river. Landslide features, such as steep scarps, grabens and tension cracks are easily visible along the valley wall. Retrogression of the slope crest has required the realignment of parts of the recreational trail just behind the slope crest.

Immediately below the flat upland area, steep scarps and grabens occupy the valley wall. Transverse ridges and cracks are also found throughout the mid-slope area. A terrace is located 25 to 30 m below the valley crest, and is traversed by a lower recreational trail. The slope below this terrace is also irregular with transverse cracks and scarps. The North Saskatchewan River is located 10 to 15 m below the terrace level. Glacial till is exposed at the toe of the slope in northern part of the park, while the remaining portion of the toe is covered by the displaced bedrock. Varying degrees of slope deterioration are evident and retrogressive slumps are found in several locations.

4.1 Coal mine workings below Forest Heights Park

Several small coal mines operated within Forest Heights Park in the early 1900's (Taylor 1971). These mines have had cave-in and subsidence problems in the past. Coal was extracted from two coal seams, the Weaver seam and the Clover Bar seam, located 30 m and 70 m below the slope crest respectively (Godfrey 1993). Although there were several mines in the study area, only the Dawson mine worked the deeper Clover Bar seam, while the other mines worked the shallower Weaver seam (Taylor 1971). Figure 12 presents the extent of the mine workings, along with current major slope features.

4.2 Geotechnical investigation

A site investigation and instrumentation program was conducted by the City of Edmonton in the fall of 2004 where continuing slope movements were affecting both the upper and lower recreational trails. The field investigation program included sampling and coring of the glacial and bedrock deposits behind the valley wall and below the lower trail (SoeMoe et al. 2007). To monitor the slope movements and the groundwater regime at the site, standpipes, vibrating wire piezometers, pneumatic piezometers and inclinometers were installed behind the valley crest and at the toe of the slope. The stratigraphic profile behind the valley wall can be summarized as follows:

- Below the flat upland area, 5 to 6 m thick lacustrine clay deposit interbedded with silt layers was identified. Borings conducted in the northern part of the park encountered a 2 to 3 m thick fill overlying the lacustrine clay deposit.
- The lacustrine clay was underlain by sand and glacial till of 9 to 10 m thickness. The sand deposit was generally dense to very dense, with moisture contents less than 10 %. The glacial till was low in plasticity and had moisture contents ranging from 15 to 25 %.
- The glacial till deposit was underlain by Upper Cretaceous bedrock comprising clay shale and sandstone, interbedded with coal and bentonite seams. The clay shale was low to intermediate in plasticity, with moisture contents ranging from 18 to 22 %.

4.3 Causes of slope instability

Several factors appear to affect the kinematics and mechanisms of the Forest Heights Park landslide. The three major factors involved are discussed in the following subsections.

4.3.1 Toe erosion by the river

Most of the recent deep seated major landslides in the North Saskatchewan River Valley have occurred on an outside bend of the river, where toe erosion is more prevalent. In the Forest Heights Park landslide, slope movements continued after the construction of a protective toe berm. Field investigation revealed that the rupture surface was located above the toe berm, as was also noted at the Keillor Road and Whitemud Road Landslide Sites. It is possible that the recent slope movements at Forest Heights were the result of groundwater level changes in the displaced material.

In June of 2005, the level of the North Saskatchewan River increased above the elevation of the toe berm. This flooding event caused significant toe erosion, and tension cracks soon appeared along the lower trail as shown in Figure 13.

4.3.2 Coal mining

Coal mining below the area appears to have caused the weakening of overlying bedrock, accelerating the propagation of cracks deeper into the bedrock. This significant weakening of the bedrock would also have facilitated subsequent softening of the bedrock by allowing increased groundwater flow through the cracks, accelerating the softening processes in the bedrock. Finally, hydrostatic pressure may have built up within the cracks during periods of heavy rainfall, which in turn would significantly reduce the factor of safety of the valley wall.

Since most of the old mine workings extracted coal from the Weaver seam, located at mid height of the valley wall, it is probable that coal extraction from the Weaver seam had the greatest impact on the stability of the valley wall. The effects of mining the Clover Bar coal seam appeared to be minimal, since this seam is located 25 m below the failure plane. The location of the coal seams together with the displaced material is shown in Figure 14.

5 LONG TERM STABILITY OF WEAK ROCK SLOPES

Case studies revealed that landslides in the North Saskatchewan River Valley present both first time slides and reactivated slides. In a first time slide, failures occur on slopes that have not been sheared by previous movement. Old landslides were found to be susceptible to reactivation by small changes in slope geometry or groundwater conditions. In all cases, river valley landslides in weak rocks occur by a combination of various factors, including toe erosion by the river, the effects of residential development behind the slope crest including the rise of groundwater levels, and softening of the bedrock at the valley wall.

In order to determine the pre-failure and post-failure characteristics of the various landslides along the North Saskatchewan River Valley, available information from five landslides, Whitemud Road Landslide (SoeMoe et al. 2006), Keillor Road Landslide (SoeMoe et al. 2005), Forest Heights Park Landslide (SoeMoe et al. 2007), Lesueur Landslide (Cruden et al. 2002; Thomson 1971) and Grierson Hill Landslide (Martin et al. 1998; Martin et al. 1984), were compiled and summarized in Table 1. This table summarizes the type and thickness of overburden materials, bedrock thickness above the surface of rupture, and the observed movements during pre-failure, major failure and post-failure time period.

Depending on the type and thickness of overburden material, landslides in weak rocks along the North Saskatchewan River valley can be divided into 3 types:

- Thick overburden above the surface of rupture (30 to 41 m thick)
- Thin overburden above the surface of rupture (15 to 21 m thick)
- No overburden

The case studies revealed that post-failure movements are dependent on the thickness and type of overburden materials above the surface of rupture. Both the Whitemud Road Landslide and Lesueur Landslide had thick overburden materials and, for both of these slides, the major failure event was completed in one day. Even though no detailed records exist concerning the duration of the major failure in Grierson Hill Landslide, it is estimated that major failure may have taken several days to several months. In bedrock-dominated slopes, the major failure event appears to take a longer time to complete as observed for the Keillor Road Landslide, where the major failure event took more than two years to complete.

Post-failure movements depend on various external conditions which can increase or decrease with time. Major factors for the post-failure movements are toe erosion by the river, groundwater level rises due to precipitation and snow melt, and changes in slope geometry. Martin et al. (1998) described long term monitoring of Grierson Hill Landslide and found that rate of movements were significantly reduced after the construction of stabilization measures. The summary of post-failure movements of three landslides is presented in Table 2

6 CONCLUSIONS

Landslide mechanisms and kinematics were studied for three case histories along the North Saskatchewan River Valley. The slope failures were caused by a combination of different factors: toe erosion by the river, the effects of residential development behind the slope crest including the rise of the groundwater level, and softening of the bedrock. Case studies also revealed that river valley landslides in weak rocks developed in stages starting as a minor toe failure, and retrogressing upslope, resulting in major failure at a later stage. Landslide stages observed in the North Saskatchewan River Valley can be described as follows;

- Pre-failure slope movement can be characterized by minor failures at the toe and the mid-slope area. In Whitemud Road and Keillor Road landslides, pre-failure slope movements ranged from 2 to 12 years.
- During the major slope failure, the main body translates along the surface of rupture and a distinct graben feature appears at the head of the displaced material due to subsidence. In Whitemud Road Landslide, most of the major movements completed within one day. However, Keillor Road Landslide took more than two years to complete the major movements.
- After a major failure, displaced material rests on the rupture surface and the factor of safety improve with the new slope configuration. During this period, some changes in the external condition such as increase in groundwater level, changes in slope configuration and loading at the slope crest can reduce the factor of safety to below unity. In Forest Heights park, landslide still active more than 100 years the major failure.

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Table 1 Summary of slope movements for major river valley landslides in Edmonton

Landslide Name	Overburden and Bedrock Thickness above failure plane (m)	Pre-failure	Major failure	Post-failure movement	Pre-failure Slope Angle	Post-failure Slope Angle
Whitemud Road Landslide (1999)	Fill – 4 to 7 Kames – 20 to 25 Till – 6 to 9 Bedrock – 5 to 8	1997 to 1999	24 hours	1999 to present	31 to 38 °	22 to 24 °
Keillor Road Landslide (2002)	No overburden Bedrock – 33 to 36	1989 to 2001	2002 to 2004	2004 to present	40 to 45 °	23 to 27 °
Forest Heights Park Landslide (1900s)	Clay – 7.0 to 10 Till – 8.0 to 11 Bedrock- 28 to 32	N/A	N/A	1900s to present	N/A	15 to 18 °
Lesueur Landslide (1963)	Clay – 5 to 8 Till – 6 to 7 Saskatchewan Sand & Gravel – 6 to 8 Bedrock - 12	April 1963 to Sept 1963	24 hours	1963 to present	23 to 30 °	16 to 18 °
Grierson Hill Landslide (1901)	Clay – 8 to 10 Till – 6 to 8 Bedrock 27	N/A	Several days to years	1901 to present	29 to 35 °	11 to 12 °

Table 2 Summary of observed post-failure rate of movements

Landslide	**Post-failure movements (Toe)**	**Post-failure movements (Crest)**
Whitemud Road Landslide	1.5 to 7 mm/month	25 to 30 mm/month
Keillor Road Landslide	125 to 250 mm/month	350-850 mm/month
Grierson Hill Landslide	1 to 5 mm/month	0.75 to 2.2 mm/month

Figure 1 Keillor Road landslide (May 2005, the City of Edmonton)

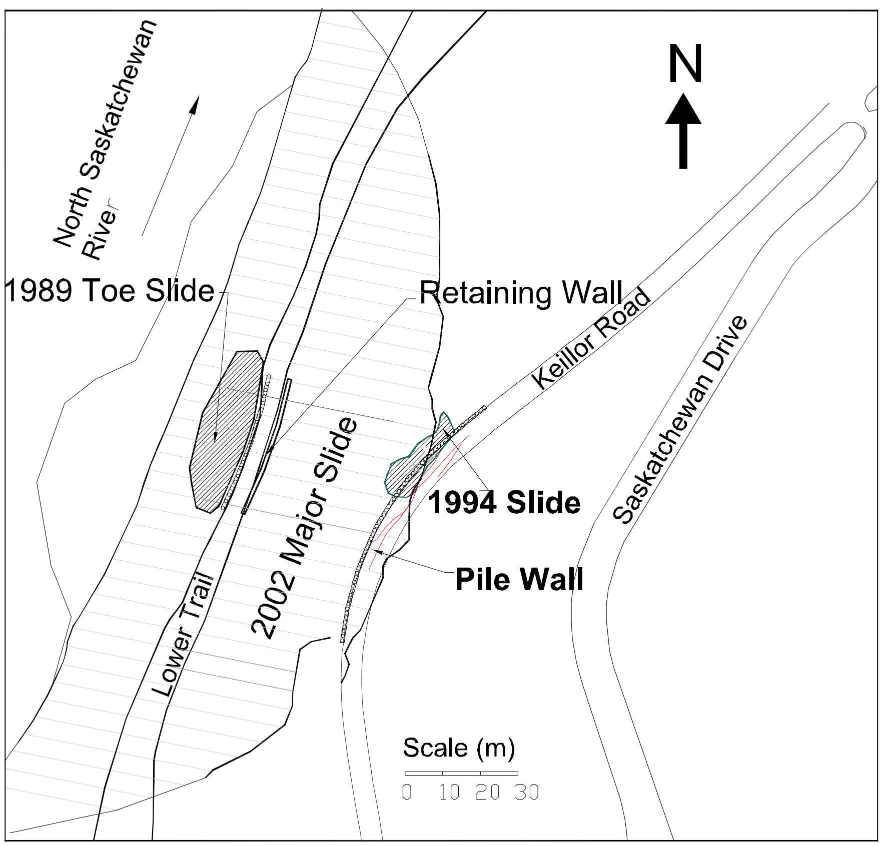

Figure 2 Map of slide area and site investigation plan

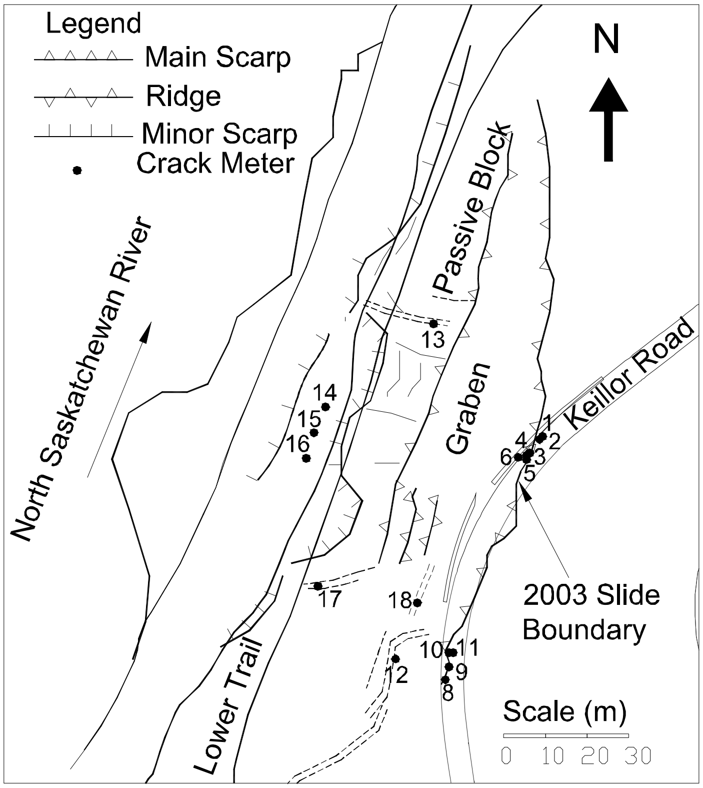

Figure 3 Landslide map of Keillor Road (2003)

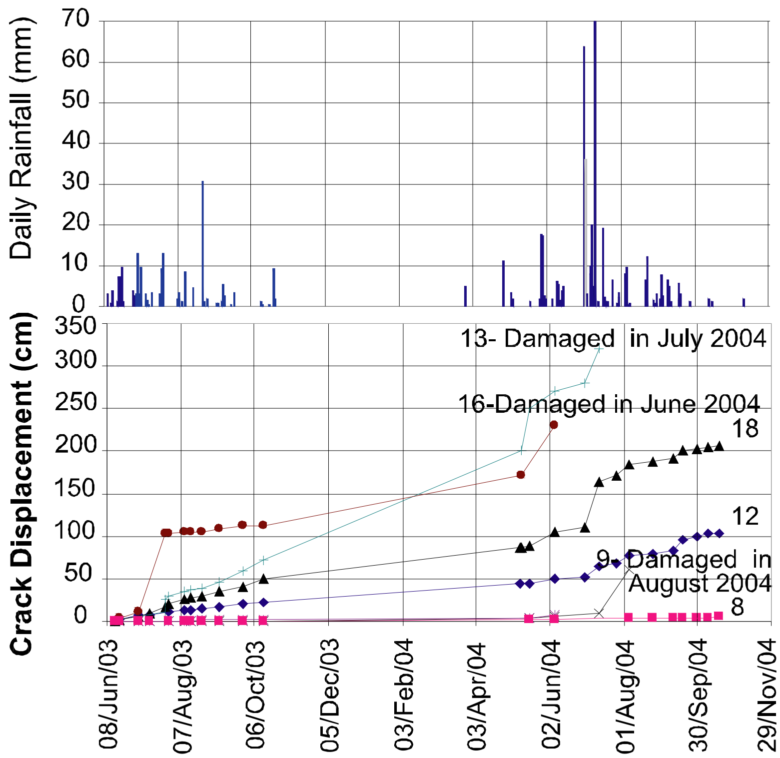

Figure 4 Horizontal displacements of crack meters

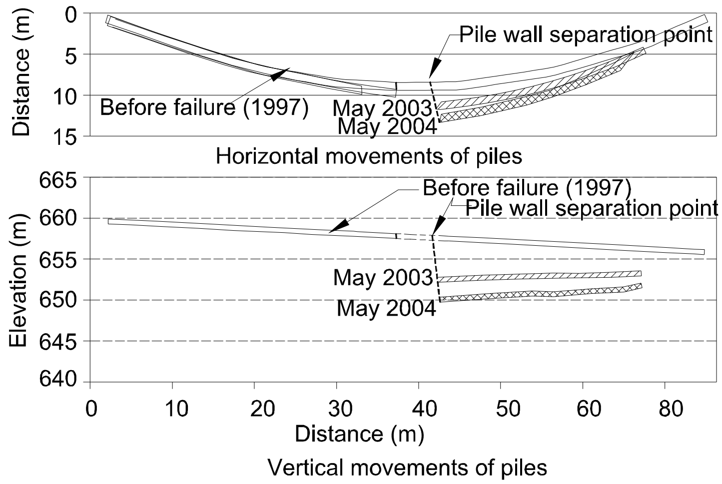

Figure 5 Movements of the cast-in-place piles

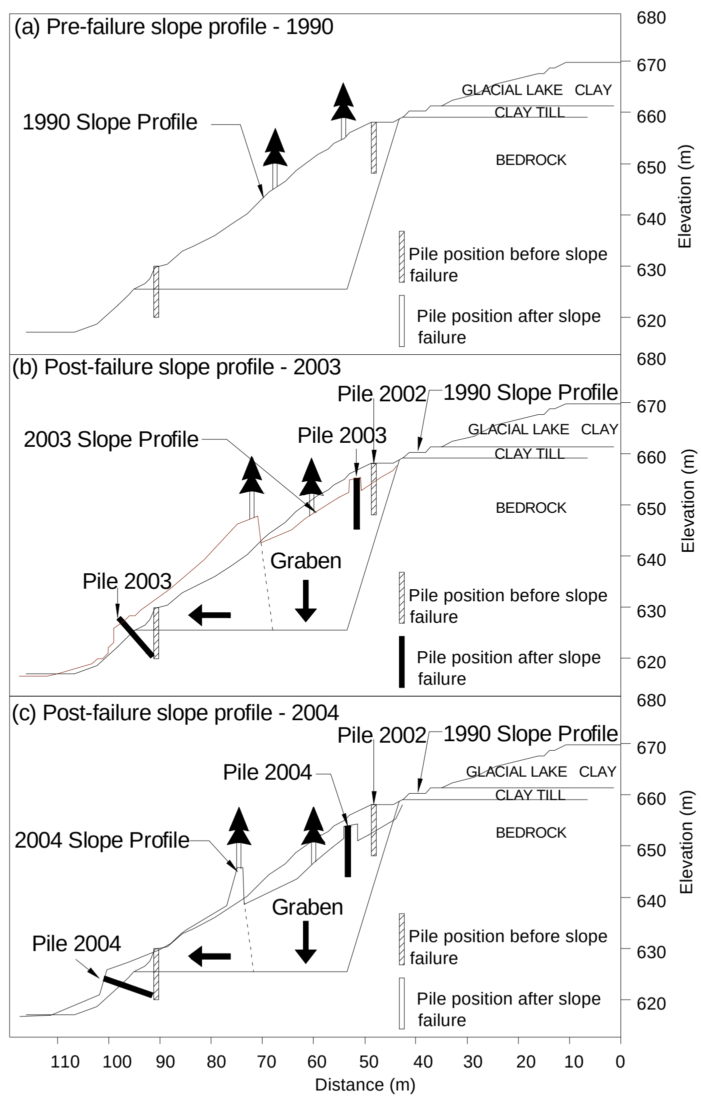

Figure 6 Slope profile survey (Pre-failure, 2003 and 2004)

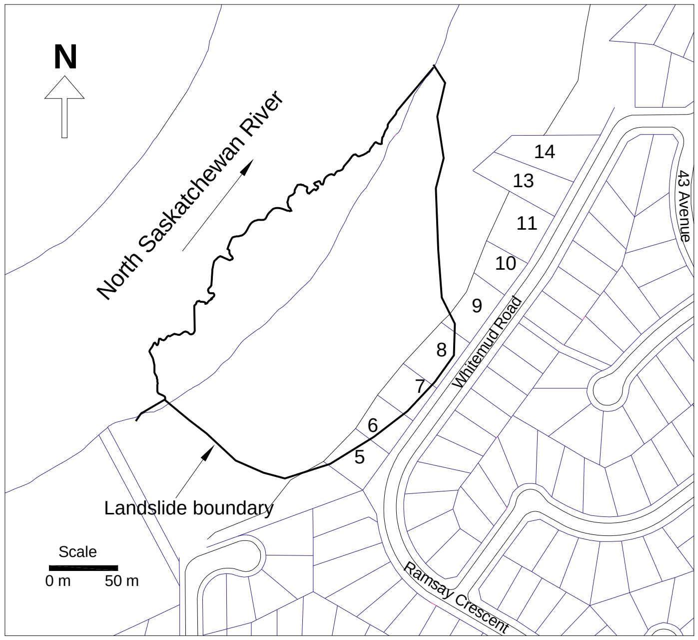

Figure 7 Location of Whitemud Road slide

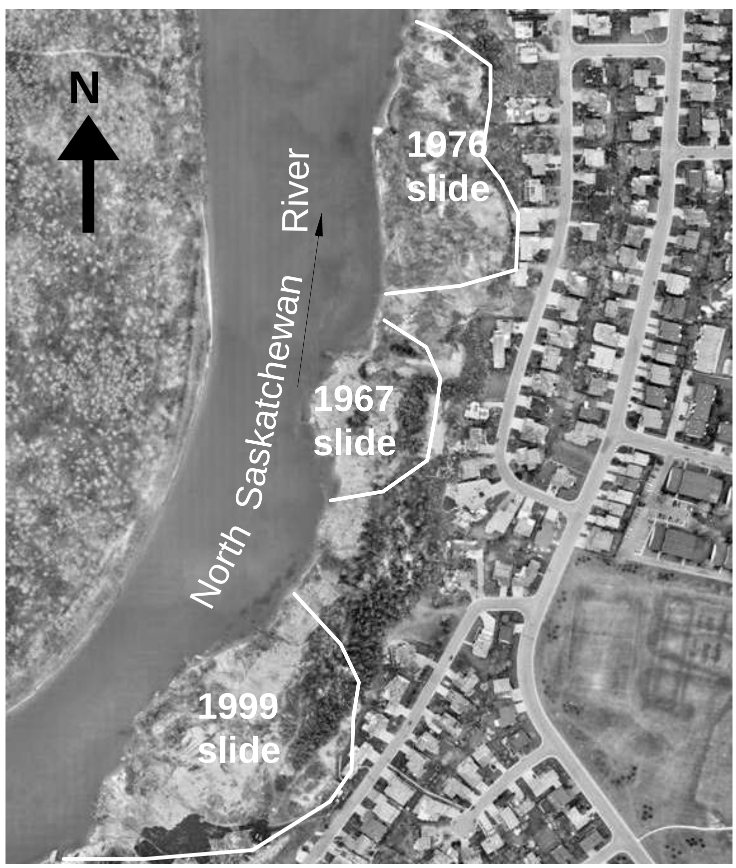

Figure 8 Landslides along Whitemud Road (May 2002, City of Edmonton, Line 17E, Scale 1: 5000)

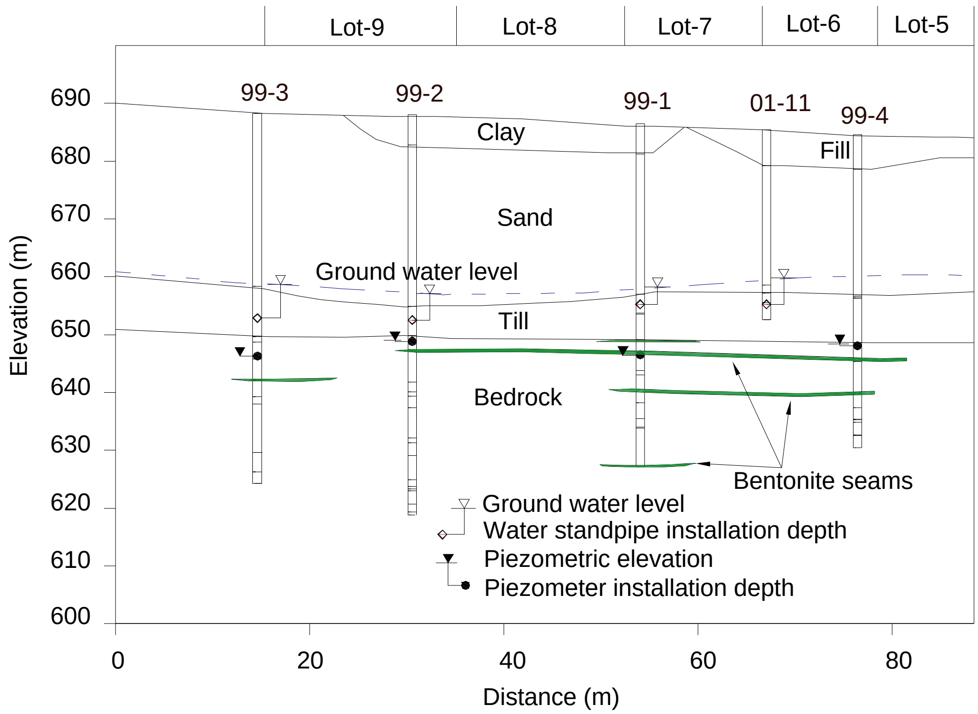

Figure 9 Cross-section along Whitemud Road

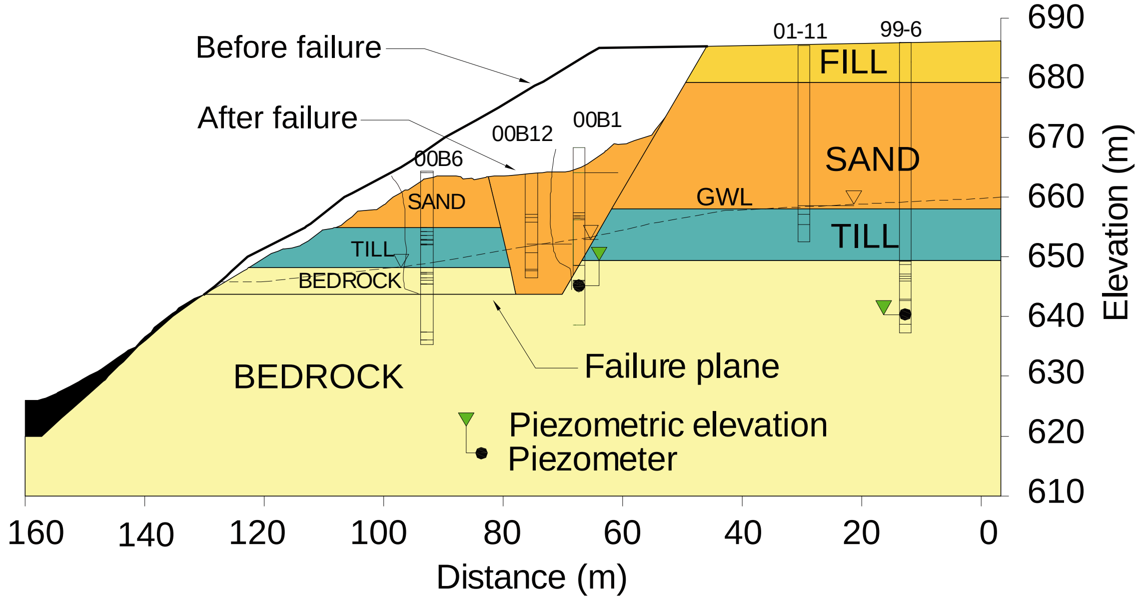

Figure 10 Pre and post-failure cross section of Whitemud Road Landslide

Figure 11 River valley view of Forest Heights Park

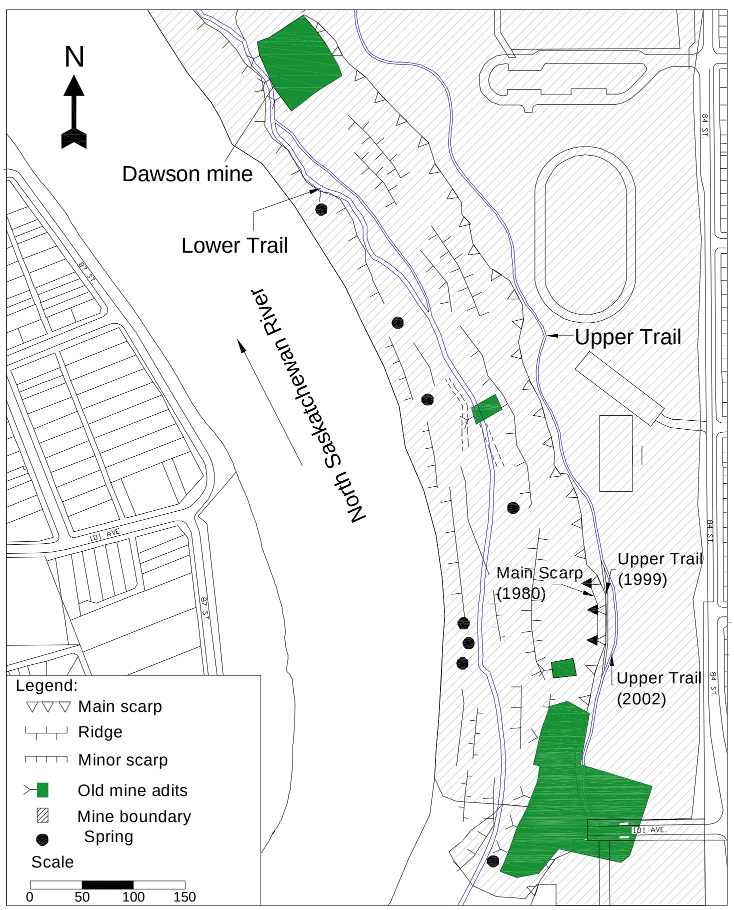

Figure 12 Map of Forest Heights Park (modified after Taylor, 1971)

Figure 13 Tension cracks in the lower trail

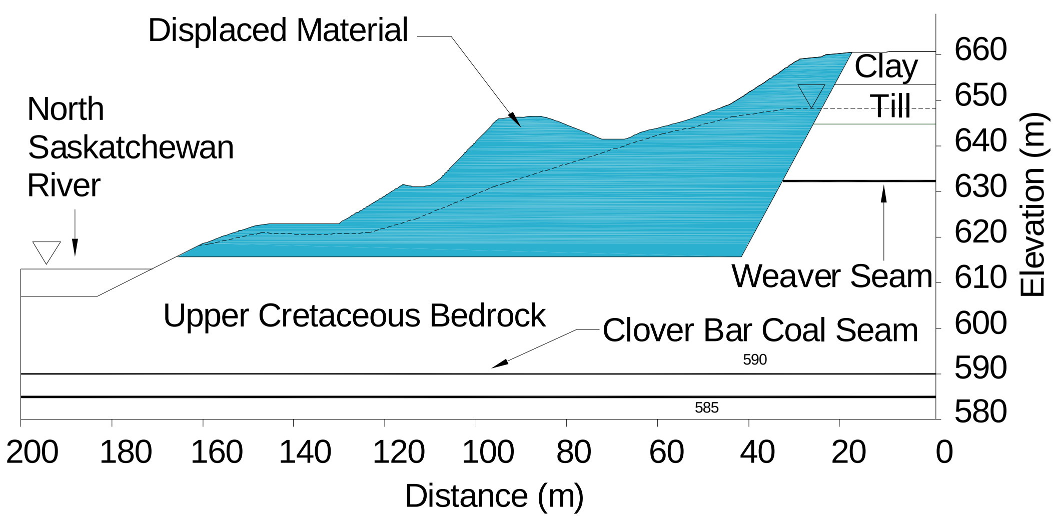

Figure 14 Cross section of the valley wall together with coal seam elevations