35 Years Activity at the Lesueur Landslide Edmonton, Alberta

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ABSTRACT

The Lesueur landslide occurred on 3 September 1963 on the outside of a meander of the North Saskatchewan River in northeast Edmonton. The displaced volume was 0.76 Mm^3 of Pleistocene deposits and underlying Upper Cretaceous mudstones. The trigger of the landslide is believed to be accelerated erosion of the slope toe caused by dumping of mine waste on the inside of the meander.

Surveys in 1964, 1971, 1992, 1995, 1997 and 1998 have documented continued slope movements. The main scarp grew from 7.5 m on 4 September 1963 to 13.9 m in 1995 but retrogressed only 3 m. The displaced material extended up to 24 m into the North Saskatchewan River. When the forward motion of the passive block of the translational slide ceased to be driven by the sinking of the active block, river erosion caused rotational sliding of the displaced material on the surface of separation.

INTRODUCTION

The first investigations of the Lesueur landslide (Painter, 1965, Pennell, 1969, Thomson 1971a, b) focussed on the determination of parameters for back analysis of the slope's stability. Since then, this reactivated, retrogressive, rapid translational rock slide has continued to move as a slow earth flow. This behaviour invites comparison with the three models of landslide activity reported by Hutchinson from sea cliffs in London Clay (1973, 1995). Our more recent suggestion (De Lugt et al., 1993) of a method of estimating safe setbacks from the crests of river valley walls on the Interior Plains incorporated the third of Hutchinson's models, the abandoned slope. Our estimates of setbacks would be made more precise by more detailed knowledge of the slope processes that follow the rock slide. Here, we report the results of 35 years' activity during which natural processes proceeded with little interference.

We first describe the landslide, then the surveys and analyses that have been carried out. Our nomenclature follows Cruden and Varnes (1996)

THE LANDSLIDE

The Lesueur landslide is located on the right bank of a meander of the North Saskatchewan River now on the northeastern outskirts of the City of Edmonton, Alberta (Figure 1). In April 1963, the first sign of the landslide was a small but distinct crack that arced across the lawn and terminated at the basement wall of the Lesueur house about 3 m from its northwest corner. The scarp developed and at 20:00 September 3, 1963, the scarp was 1.8 m high. At 8:00 September 4, 1963, the scarp was 6.7 m high, exposing a corner of the foundation of the house as it was cantilevered over the scarp (Thomson, 1971a, Figure 3). The landslide scarp was 50 m wide but the lateral margins diverge to 150 m at the river where the flanks of the landslide are poorly defined. The depth to the surface of rupture was determined by drilling to be 32 m. The displaced volume was estimated to be 0.76 Mm^3.

The landslide was caused by erosion of the vestiges of a low level terrace, (Thomson 1971b) and the weakening of the strata in the lower part of the slope by interbed slip due to valley rebound (Matheson and Thomson, 1973). We now consider that gravel mining operations on the north bank enhanced bank erosion by the river.

The upper walls of the slope consist of Pleistocene deposits, while the lower half is composed of an Upper Cretaceous sequence of mudstones. Glaciolacustrine silty sand overlies till which overlies Saskatchewan sands and gravels. The bedrock is Horseshoe Canyon Formation, a clay shale over a bentonitic clay shale with a bentonite, coal seam and a bentonitic sandstone (Thomson, 1971b, Figure 1). The bedrock topography (Kathol and McPherson, 1971) shows a bedrock ridge that trends north and terminates at the south bank of the North Saskatchewan River under the landslide deposits. To the west, the ridge slopes down into the low-level terrace of the North Saskatchewan, abandoned by the river 7000 years ago (Rains and Welch, 1988). To the east, the bedrock slopes into the Boag preglacial valley (Andriashek et al., 1997). Zabeti (1998) located the thalweg of the valley on the south wall of the North Saskatchewan 0.6 km upstream from Oldman Creek, about 0.7 km downstream from the Lesueur house (Figure 1). As the landslide is on the outside of a meander of the river, the toe is actively eroded. The right flank of the landslide exposed evidence of at least one previous landslide (Thomson, 1971a,

Figure 5). Other landslide scarps are clearly visible on the airphotos and Cruden et al. (1989) documented landslides from the Lesueur site downstream to Fort Saskatchewan, a distance of 30 km. Zabeti (1998) mapped 12 distinct landslides in a continuous succession from the Lesueur house east to Oldman Creek (Figure 1).

AIR PHOTO ANALYSES

The Provincial Government's collection of air photos contains 32 sets taken of the area around the Lesueur slide dating from 1924 to 1999. Six of the coverages are at scales of 1:12000 or more detailed and thus offer the opportunity of locating the slope crest with a precision of the order of metres. In addition, as the City of Edmonton expanded eastwards, its photography included the site. From 1962, 13 sorties flown for the City made available photography at scales as detailed as 1:6000.

The 1924 photography shows continuous tree cover below the crest of the bank from the terrace upstream to the mouth of Oldman Creek. On the inside of the meander, the land has been cleared but an extensive screen of trees separates farmland from the river.

The 1952 photographs, Figure 1, document substantial disturbance of the tree screen on the inside of the meander. Road access from the west has been driven to a pit at the river's edge. Ramps into the river provide access to dispose of pit waste. To the south of the pit, on the outside of the meander, a single, 200 m wide landslide, active after 1924, also constricts the North Saskatchewan's flow. The south bank crest is cuspate in plan indicating the scarps of inactive landslides along the 1.3 km of bank between the Lesueur house and Oldman Creek.

The 1962 photographs, Figure 2, taken in the year before the landslide, record further upstream expansion of mining activity on the inside of the meander; tailings have been placed in the river, perhaps as embankments to protect pits from flooding by the river. Landsliding has extended upstream on the south bank.

On the south bank, trees have been cleared around the Lesueur house to reveal the scarps of two inactive landslides, to the west and north of the house. The western landslide apparently developed before the abandonment of the slope above the low-level terrace, 7000 years ago. The northern landslide moved into the North Saskatchewan River, perhaps 200 years ago (Painter, 1965). The 1963 slide reactivated the western flank of the north landslide and the northern flank of the west landslide forming a landslide separated into western and eastern parts by longitudinal cracks (Figure 3).

Mining activity ceased in 1954. Alberta Environment records a sand and gravel lease whose operator extracted 26, 969 cubic yards (20,587 m^3) in the 5 years the pit was active. The bars of the North Saskatchewan have been extensively worked for placer gold (Morton and Mussieux, 1993) and the washed gravel produced by such an operation would have found a ready local market (Edwards, 1993). There was little demand for the fine sand which has been placed in the river.

The 1995 photographs, Figure 4, demonstrate the revegetation of the now abandoned gravel pits. Erosion of the north bank has produced a steep unvegetated toe which is apparently providing less sediment to the river than in the 1962 photos.

The south bank has seen the reactivation of three landslides after 1962, with Lesueur, in 1963, the most westerly of these. The steep bank toe shaded by trees below the Lesueur property, has been replaced in the 1995 photographs by an open fan of colluvium. Shade at the toe of the fan indicates some steepening of it by erosion; a 10 m wide cusp and the arc of the scarp of similar length facing the river demonstrate that erosion is proceeding by small landslides. The line of the toe of the slope in 1952 can be judged by projecting the tree-shaded toes from upstream and downstream of the 1963 landslide. The diffuse shaded boundary along this projection marks the downslope boundary of mature trees predating the 1963 landslide and the growing scarp formed by independent movement of displaced material on the surface of separation of the 1963 landslide, downslope of the toe of its surface of rupture.

Simple mensuration techniques on the series of air photos determined changes in the width of the river at the toe of the slide and 0.5 km upstream. The data are plotted on Figure 5. There was a dramatic decrease in the river width at the time of the landslide caused by the advance of the toe of the slide into the river. Since then the river width has steadily increased.

The observations (Thomson, T.J., 1996, personal communication) are consistent with a post-1984 increase in the width of the river to approach its 1952 width. This increase in width is accomplished by erosion of the north bank, on the inside of the meander. The south bank has encroached on the river bed beyond its 1952 position. While these data are consistent with the surveyed profiles recorded in Table 1 and plotted in Figure 5, they are relatively imprecise. Observations from 3 independent photo sorties within 5 days of one another in the fall of 1986 show a range of 10 m in locating the south bank. Besides photogrammetric variables, variation in shadows and water levels add to uncertainty about the water's edge.

We used stereo pairs of photos from 1952 at 1:12,000, 1992 at 1:10,000 and from 1986 at 1:5,000 to estimate valley crest recession as a result of the 1963 slide. The later photographs show the significant land use modifications since 1952. Buildings, a powerline and section roads are visible on all 3 sets of photographs but only one building appears in common. Furthermore ground in the vicinity of the slide is obscured in 1952 by dense tree cover; the crest of the bank is clearly visible but the toe is not. Both the crown and toe of the slide are visible in the 1986 and 1992 photography.

The photo pairs for 1952, 1986 and 1992 were compared stereoscopically, common points were selected and marked with pin pricks on the photos and the marked points and the camera fiducial marks were digitized. Image coordinates were determined with 0.2 mm standard deviation as confirmed by the subsequent least squares adjustments used to determine the ground coordinates; the resulting ground coordinates had standard deviations of 2 m horizontally and 3 m in elevation. The locations of the crests of the slope on the 1986 and 1992 photography agreed within 2 m, within the coordinate accuracies. Photogrammetric analysis indicated that the valley crest had retreated 15 m between 1952 and 1992.

SURVEYS

Reconnaissance of the Lesueur landslide in 1985 (Cruden at al., 1989) and in 1992 (de Lugt et al., 1993) revealed that there had been considerable changes in slope morphology since the landslide in 1963. The situation presented an opportunity to evaluate the changes that occurred over 30 years. A stadia survey, the photogrammetric analyses and simple mensuration on airphotos, a controlled survey of hubs on the landslide area and profiles of the river bed were all undertaken to provide adequate data which, when combined with existing information, allows a detailed analysis of the slope.

A map of the landslide based on stadia survey in June, 1995 (Figure 6) located the two rows of standpipes installed in the displaced mass during the slope investigation in 1964. The reference hubs placed during the 1964 survey have been lost in the landscaping for the present house. Fortunately, Borehole 3 (Figure 3) was found and, now allows a direct comparison of the 1965 and 1995 maps with some orientation uncertainty. However, there are still difficulties in comparing profiles of the slide (Figure 5, 6, 7). From 1964 to 1995, the considerable growth in the underbrush has made surveying difficult. Line clearing has been kept to a minimum at the request of the property owners.

Table 1.1, derived from the profiles down the centre line, shows the overall length of the landslide to have increased by 24 m by 1995. In effect, the toe of the displaced material advanced at least 24 m onto the riverbed. The changes observed in length for the intermediate dates and the changes in the location of the standpipes (Table 1.3) indicate that the movement has continued since the failure in 1963. The continuing movement is also shown by the recent drawdown bank failures. The dips of the vectors of the displacements of the standpipes (Table 1.3) are downward in the depletion zone and largely horizontal movements in the accumulation zone. The scarp height in June 1964, 7.6 m, had increased to 13.9 m in 1995. Calculations of intermediate rates shows a slowing of this increase in height.

The 15 metre retreat of the crest of the slope at the crown of the slide (Figure 7) agrees with the photogrammetric determination. At the time of failure, the scarp retreat was 12 m,. in the interval from 1963 to 1995 the top of the scarp has retreated only 3 m. The scarp is protected by a dense growth of scrub brush, wood chips and small branches dumped over the scarp. These inhibit erosion by rain and spring runoff although the lake sediments are erodible. The efficacy of the protection is born out by the small accumulation of colluvium at the base of the scarp.

The movement of the standpipes on the right side of the slide, the G series, is much greater than those on the left side, the D series. This difference in movement suggests that the displaced mass is separating along the distinct cracks mapped between the G and the D series (Figure 3).

The largely horizontal movement of the lower standpipes, G2, G3, G4, the seepage zones near the toe, the flattening of the lower slope and the continued forward movement of the toe may be interpreted as a change of movement mechanism from the initial translational sliding mode to that having flow characteristics, a phenomenon that has been observed at Edgerton, 200 km to the east (Cruden et al, 1995). The depletion and accumulation zones are visible in Figure 7.

The river channel was investigated by echo sounding, obtaining 6 profiles of the river bed (Zabeti, 1998, Figure 3.5). Two typical profiles, located on Figure 4, are shown on Figure 8. The large exaggeration of the vertical scale emphasizes that on the inside of the meander, the river bed slopes steepen northwards. Their steepness is a reflection of the river being forced northward by the advance of the toe into the river. So, the widening of the river shown on Figure 5 is accompanied by erosion of both banks.

Four hubs placed along the toe of the slide in October 1996 were located again by precise survey in October, 1997 to determine their movement. At these times, the distances from the hubs to the river bank were measured (Table 2). The situation is shown in the sketch on Figure 9 and the hubs are located on Figure 6 which also shows movement vectors for other times. Site observations show that the erosion of the river bank is largely the result of undercutting and small rapid drawdown failures. Hub R6 is at the downstream tip of the landslide and is protected by the advance of the toe into the river. While these vectors show bank erosion is locally variable, rates may reach 4 m/year.

SLOPE ANALYSES

Back analyses were carried out on Profiles B-B, and D-D (Figure 3) and through the D series standpipes. The slip surface for these analyses was taken to comprise most of the lower part of the original slip surface (Figure 7), a downward extension of the present scarp and a transition section between these as determined by judgment. The soil data for the analyses were adapted from Thomson (1971b).

One of the difficulties in analyzing this landslide arises from the amount of displacement that has taken place. The lake sediments may be in contact with till, the till with the sand and gravel and the sand and gravel with the Upper Cretaceous clay shale. The contacts of unlike materials place choices of the angles of shearing resistance in the realm of judgment. The lake sediments and the till are stiff and have a low moisture content so the angle of shearing resistance was taken as close to peak values. Similar assumptions were made for the sand and gravel and till. The sand and gravel was considered to mix with the clay shale such that an angle of shearing resistance of 17 degrees, near the peak value for the clay shale, would be appropriate. Along the lower part of the slip surface, a residual value for the bentonitic clay shale was adopted due to the influence of bentonite on the angle of shearing resistance. The advance of the toe from its preslide position to its location in 1995 is shown on Figure 7 and represents a lengthening of the slip surface. The displaced material is broken-up clay shale and saturated, hence its residual angle of shearing resistance was considered to be appropriate. Following Thomson, (1971a), the cohesion was taken as zero everywhere. The results of the analyses show factors of safety range from 0.9 for Profile D-D to 0.99 for Profile B-B (Figure 3). It is likely that the water table varies across the landslide, but these factors of safety are consistent with continuing movements.

DISCUSSION

Our observations of the Lesueur slide are sufficient to distinguish three stages in the evolution of this complex translational slide.

The first stage lasted only the few hours on the 3rd and 4th of September, 1963, when rapid movement formed the graben at the head of the main body and pushed the foot of the landslide into the North Sasktachewan River. In the next stage, the slow to very slow sinking of the active block was accompanied by the very slow advance of the foot into the River. This stage ended about 1992 when the downward driving motion of the active block halted, possibly because the block now rested on the horizontal part of the rupture surface.

In the third stage of movement the passive block was no longer driven forward into the river by the sinking active block. So, erosion by the river steepened the slope of the accumulation of the displaced material at the toe of the slide and triggered small rotational slides on the surface of separation.

Other historic translational landslides in Cretaceous strata in Alberta have passed through similar stages in intervals of the same order of magnitude; the Grierson Hill landslide has been moving for almost 100 years, its evolution slowed by successful stabilization works (Martin et al., 1998), the Mackay River slide (Dewar and Cruden, 1998) developed rotational slides at its toe 22 years after its first movement.

Extrapolating the trends seen in the third stage of movement leads to a fourth stage initiated when all the displaced material on the surface of separation has been removed by river erosion. Then continued retrogression of the crown can be expected with displaced material accumulating as a talus at the head of the landslide. So the slope should become similar to that seen in the 1962 photos, with eroded bedrock at the toe of a slope which steepens towards its crest. The slope will then have completed a cycle of changes, a concept suggested by Hutchinson (1973) for London Clay and documented in Canada by Williams et al., (1979) on the Ottawa River and Quigley et al., (1977) on Lake Erie's north shore bluffs.

Differences among the stages of the cycle might arise from differences in stratigraphy, climate and geomorphic setting. For instance, Hutchinson's marine cliffs on the Isle of Sheppey, U.K. are cut in weak Tertiary mudstones, the banks of the Ottawa River are eroded in Champlain sea deposits and the north shore bluffs on Lake Erie develop in till. The contrast between rotational slides in these relatively uniform deposits and the translational slides in Alberta may result from the weak bentonites in the Upper Cretaceous rocks here.

All four sites lie within the same morphoclimatic zone - Budel's ectropical zone of abated valley formation (Budel, 1982, Figure 13, Doornkamp, 1986, Figure 2.6). The climate in Edmonton is towards the colder and drier margins of the zone, both factors which tend to reduce rates of weathering. The evidence of the 1924 photographs is that natural rates of erosion of the toes of slopes along the North Saskatchewan River valley are compatible with the weathering rates of the natural materials. Slopes might then retreat following Hutchinson's first model in which colluvium is removed at the toe of the slope at about the rate it arrives there (Hutchinson, 1973).

The landslide occurred during a relatively dry period that continued for the next 8 years to 1971. Since then precipitation has tended to be above the long term average. The continued movement during the extended drier period suggests that ground water also softened the displaced material played an important part. The original house had and the present house has a septic tank system to dispose of waste water, these systems may contributed to groundwater flow. This contribution is also suggested by the two seepage zones, one on either flank. Both these seepage zones were active during the summer of 1995; they are shown on the map produced by the stadia survey (Figure 6).

Dumping of the sand from the gravel pit over the north bank of the river appears to have triggered a substantial increase in rates of toe erosion on the south bank of the river. Hutchinson's second model requires a rate of erosion considerably in excess of the rate of weathering to trigger a landslide.

Table 2 contains a summary of rates of erosion, Dr, slope height, H, and calculations of the dimensionless parameter of the rate of slope recession, Dr/H, suggested by Hutchinson (1973). Typical values range from 1.8 to 6.7% per year with a mid-range of 4.2%. If the Lesueur slope were eroded at the mid-range rate, 1.3 metres would have been removed from the toe annually. This rate is over four times rates of erosion recorded below Type 1 slopes in the area (De Lugt et al., 1993) but substantially less than local rates of erosion recorded at the tip of the

Lesueur landslide in 1996-98 (Zabeti, 1998).

There is evidence of previous transitions from Type 1 to Type 2 recessions in the area. At the Lesueur site, the exposed right flank of the present landslide revealed a previous landslide (Thomson, 1971a). At the Edgerton landslide, an old graben was observed (Cruden, et al., 1995). It appears that different Hutchinson cycles of activity may occur, triggered by different rates of toe erosion at different times at the same site.

When, over the years, the river erodes the toe of the slope to its location before the 1963 slide and the main scarp retreats, the overall slope angle will approach 17 degrees, close to the ultimate slope angle (de Lugt et al., 1993) for the stratigraphy comprising the slope. Further landslides might then be caused if the river rapidly erodes the bank or the water table rises. A rise of the water table is likely if the area is developed to a higher density of occupation, (Hamilton and Tao, 1977). An increased rate of toe erosion has been triggered by human activity, natural triggers might include forest fires, increased river flows and downstream migration of meanders.

CONCLUSIONS

The reactivation of the Lesueur landslide in 1963 was largely triggered by anthropogenic causes, most obviously by the dumping of mining wastes over the opposite bank of the North Saskatchewan River.

The landslide has continued to move after its initial failure at rates comparable to the rates of fluvial erosion of the toe of the landslide deposits. The pattern of movement is significantly different from the models proposed by Hutchinson for London Clay. The main scarp has grown in height without substantial retrogression as the active block sank into the graben. The displaced material of the landslide has broken up and moved subhorizontally as a slow earth flow. As downward movement of the active block checked, the river eroded and steepened the tip of the accumulation causing further sliding on the surface of separation.

While river erosion has now begun to reduce the accumulation of displaced material from the landslide, the site history suggests that the time between major retrogressions of the main scarp may be hundreds of years under natural conditions. As Hutchinson (1973, p. 8) remarked about sea cliffs in southeast England, "the cliffs were pushed from Type 1 to Type 2 behaviour by temporary but severe increases in erosion intensity and accompanying pore-pressure perturbations".

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Table 1

Observations of the Lesueur Landslide

1. Borehole 3 to river bank along B-B' (Figure 3)

	Distance, m.	Cumulative change, m	rate, m/yr.
August, 1963	89		
June 1964	98	9	10.0
March 1971	100	11	0.29
October 1992	104	15	0.19
July 1995	113	24	3.0

2. Scarp Height

	m	Cumulative change, m	
September 4, 1963	6.7		
June, 1964	7.6	0.9	1.0
March, 1971	10.0	2.4	0.22
October, 1992	13.5	5.9	0.16
July, 1995	13.9	6.3	0.15

3. Changes in standpipe locations from June 1964 to July 1995 (Figures 3, 6)

Standpipe	Horizontal, m	Vertical, m	Dip Angle of Vector
D1	3.8	-2.1	28.9°
D2	1.1	-1.6	55.5°
D3	5.3	-1.9	19.7°
G1	11.7	-4.3	20.2°
G2	16.0	-2.2	7.8°
G3	11.0	-1.0	5.2°
G4	10.0	-1.2	6.8°

Note: Standpipes D1, D2, G1 and G2 remained essentially vertical, D3, G3 and G4 were tipped downhill at angles exceeding 45°.

Table 2:

Toe Displacements, X, measured by the control survey and bank erosion, Y obtained by the erosion survey, Figure 9. Units are metres, displacements towards the river are positive.

Hubs on Figure 6	Initial distance between hub and river bank, P	Distance between hub and the river bank S			Bank erosion Y	Displacement of hub Q	Toe Displacement X
	Oct. 96	Oct. 97	June 98	Aug. 98	Oct. 96-Oct. 97	Oct. 96-Oct. 97	Oct. 96-Oct. 97
R7	5.2	1.2	0.9	0.8	4.0	0.82	-3.18
16	2.4	1.0	0.8	0.6	1.4	1.06	-0.34
15A	5.0	2.3	1.3	Eroded	2.7	0.73	-1.97
R6	1.0	0.9	0.9	0.9	0.1	0.05	-0.05

Table 3

Rates of erosion at toes of slopes

Site	Slope height, H, m.	Rate of erosion, Dr, m/a	Dr/H, %/a
Ottawa River, Williams et al. (1979)	9-14	0.35 - 0.4	2.9
Lake Erie Quigley et al. (1977)			
Patrick Point	27	0.6	2.2
Iona	34	1.4	4.1
Pumping Station	42	2.8	6.7
Geography	42	2.0	4.8
Isle of Sheppey Hutchinson (1973)			
9 sites	32-51	0.9 - 2.15	1.8 - 6.7
Lesueur This paper	32	(Estimated) 1.3	(Estimated) 4.2

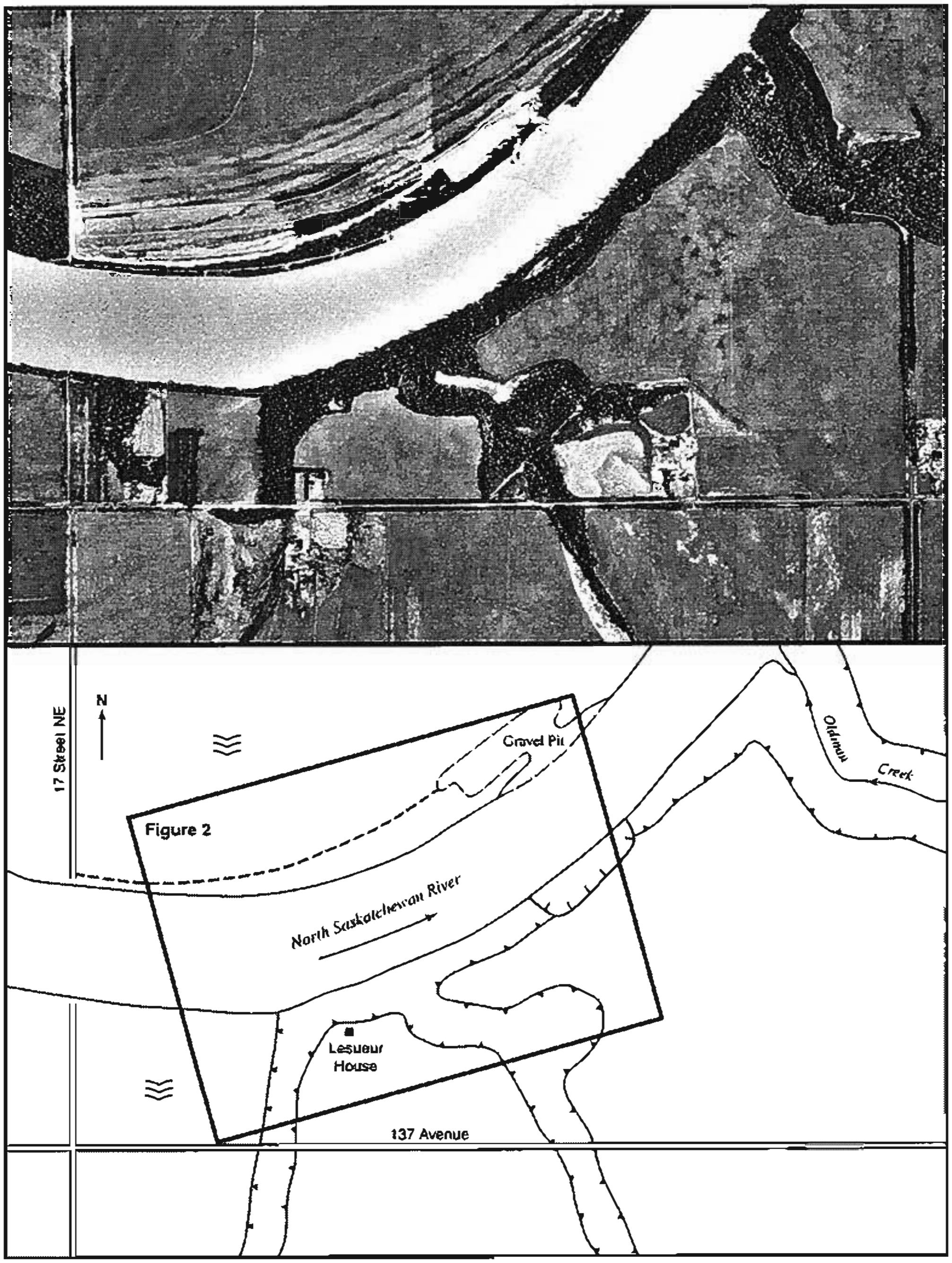


Figure 1. Part of Alberta Government airphoto AS4-275 nominal scale 1:11600, taken in 1952. The crossroads, 17 Street NE and 137 Avenue on the overlay is at 53° 36' latitude and 113° 19' longitude now within the City of Edmonton. The overlay key follows Dearman et al. (1972).

Figure 2. Part of City of Edmonton airphoto YC479-81, nominal scale 1:6000 taken in 1962. Location shown on Figure 1.

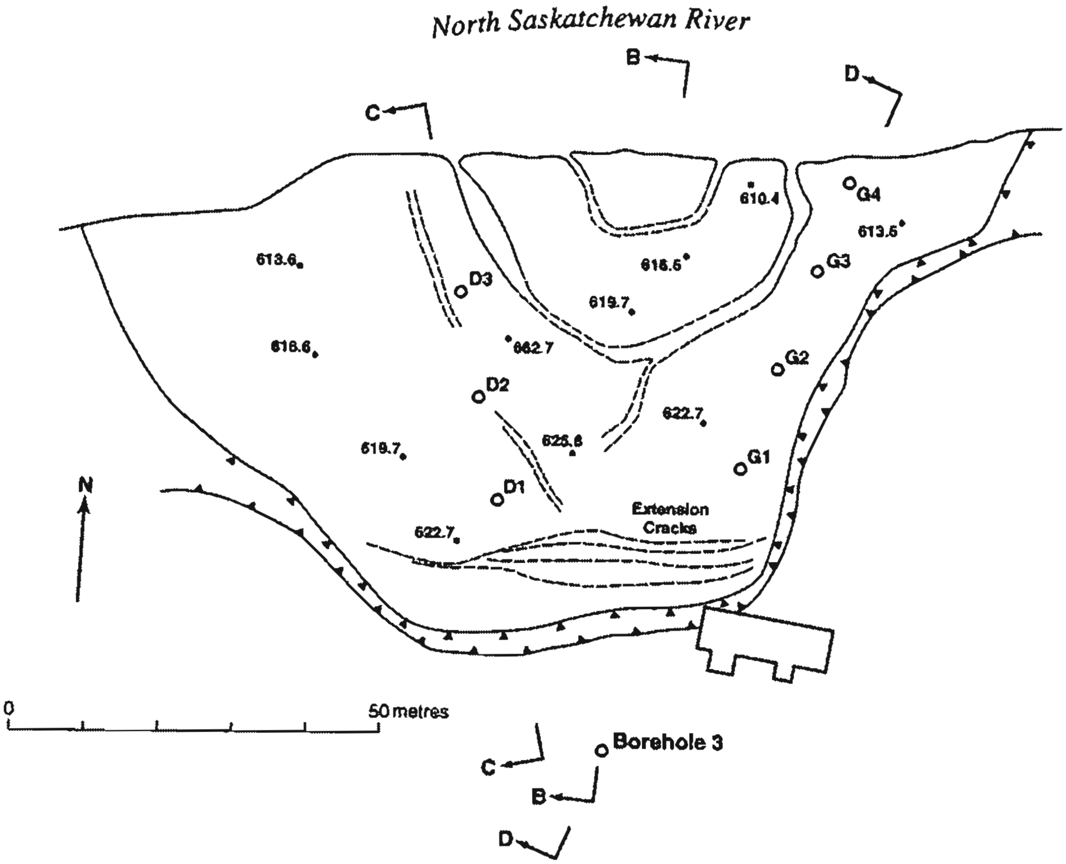


Figure 3. Map of the Lesueur landslide in 1964 based on Painter (1965, Figure 2). Spot heights are in metres above sea level.

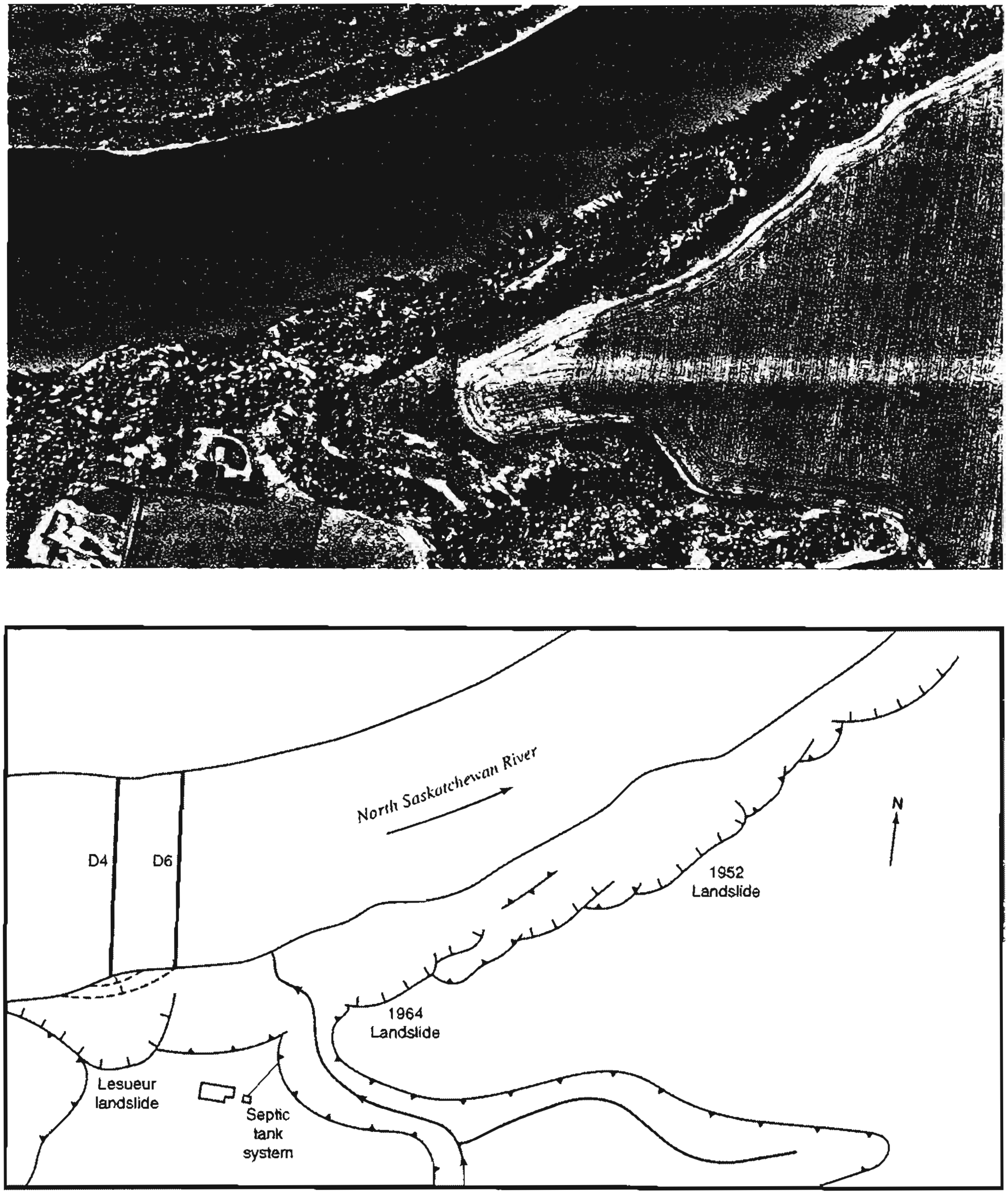


Figure 4. Part of City of Edmonton airphoto ED9511-62 nominal scale 1:5000 taken on 13 May 1995.

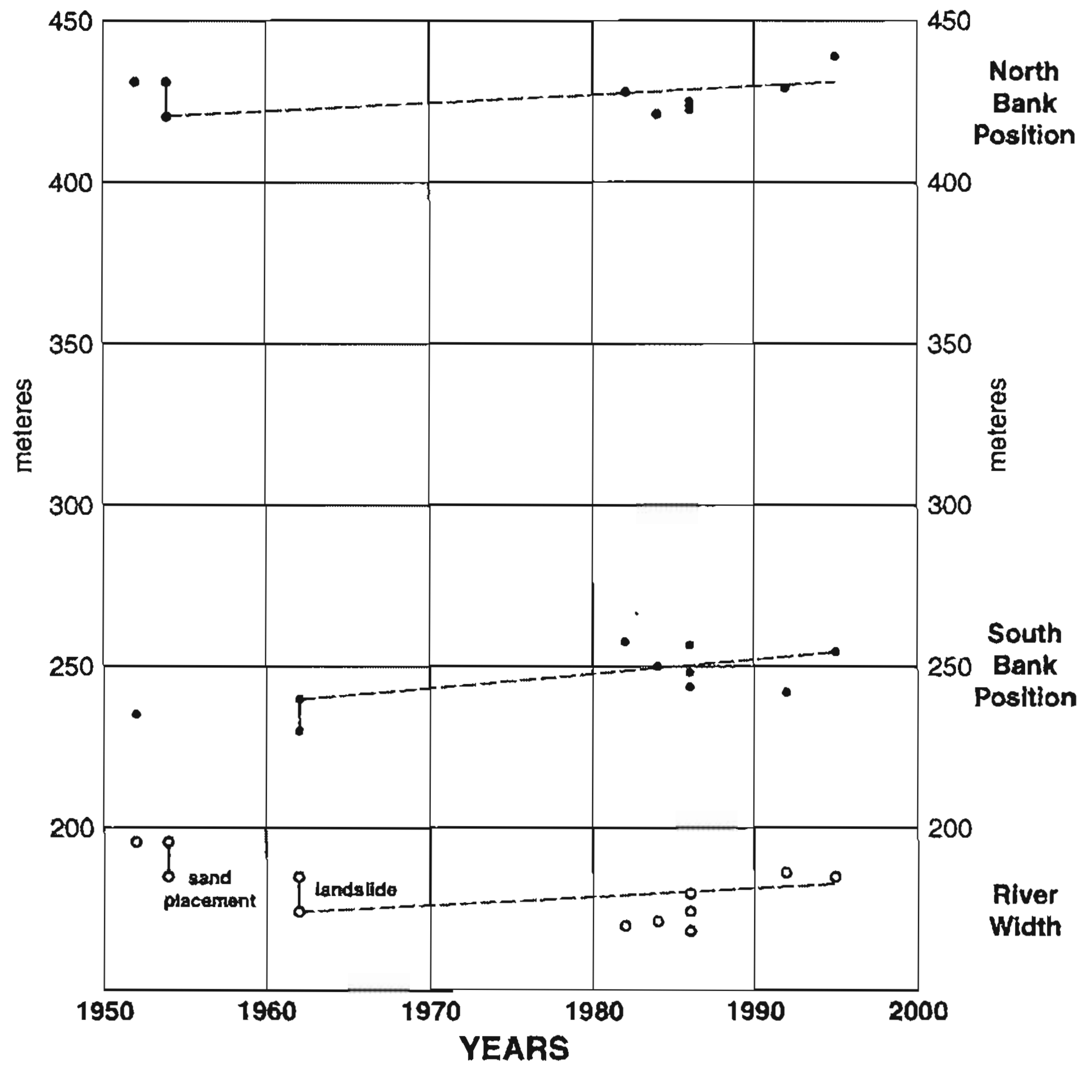


Figure 5. Estimates of river width (circles) and bank position (dots) by mensuration of airphotos (scaled from a grid using 17 Street NE and 137 Avenue as axes). Units are metres. Dashed lines are interpreted trends.

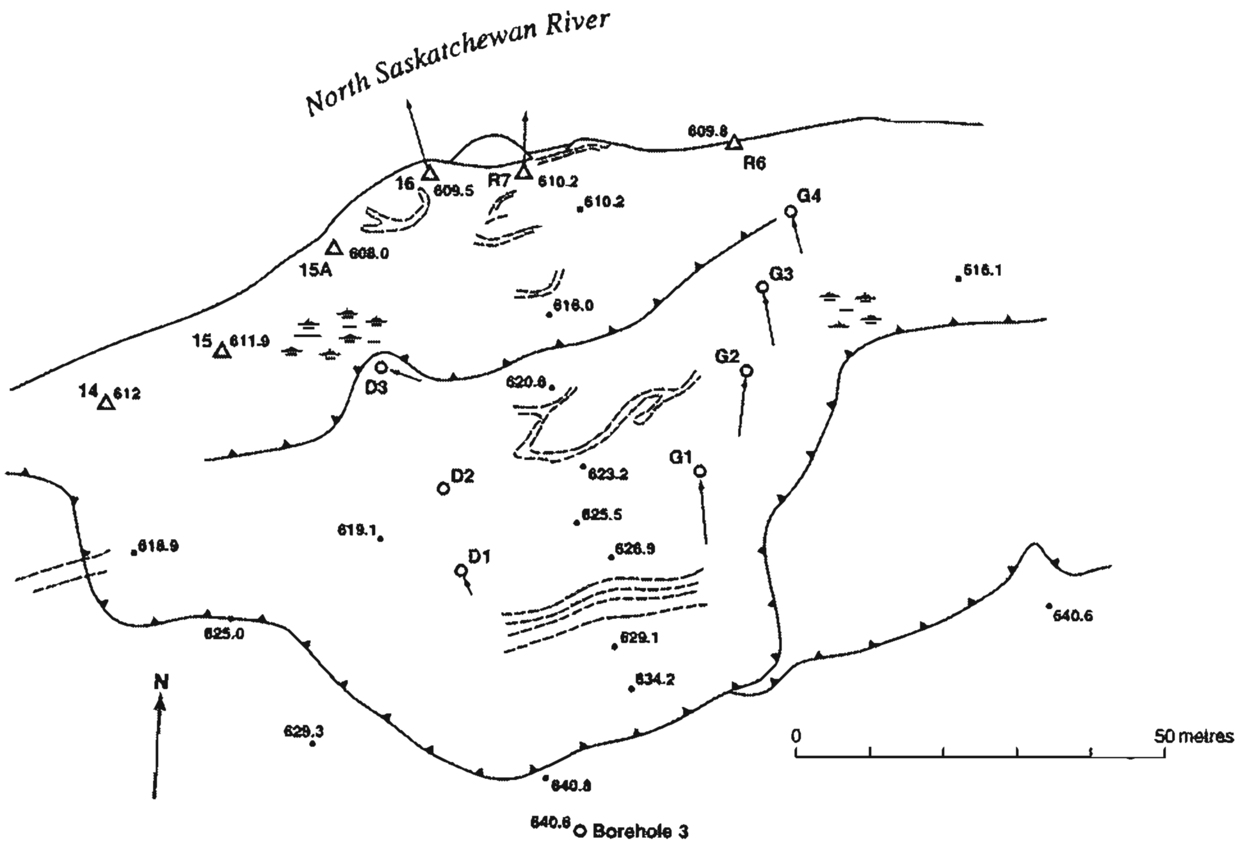
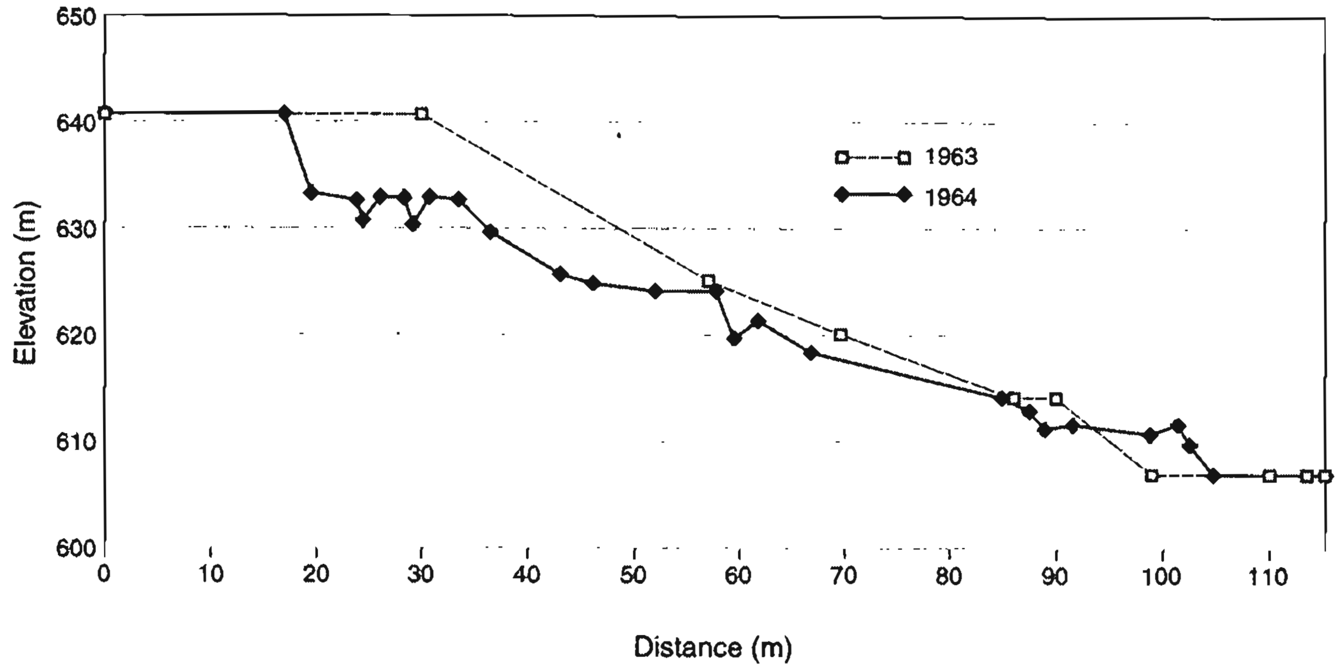


Figure 6. Map of the Lesueur landslide in 1995 showing standpipe vectors (D1, D2, D3, G1, G2, G3, G4) exaggerated 10x and new hub locations for erosion surveys, vectors exaggerated 100x. Spot heights are in metres above sea level.



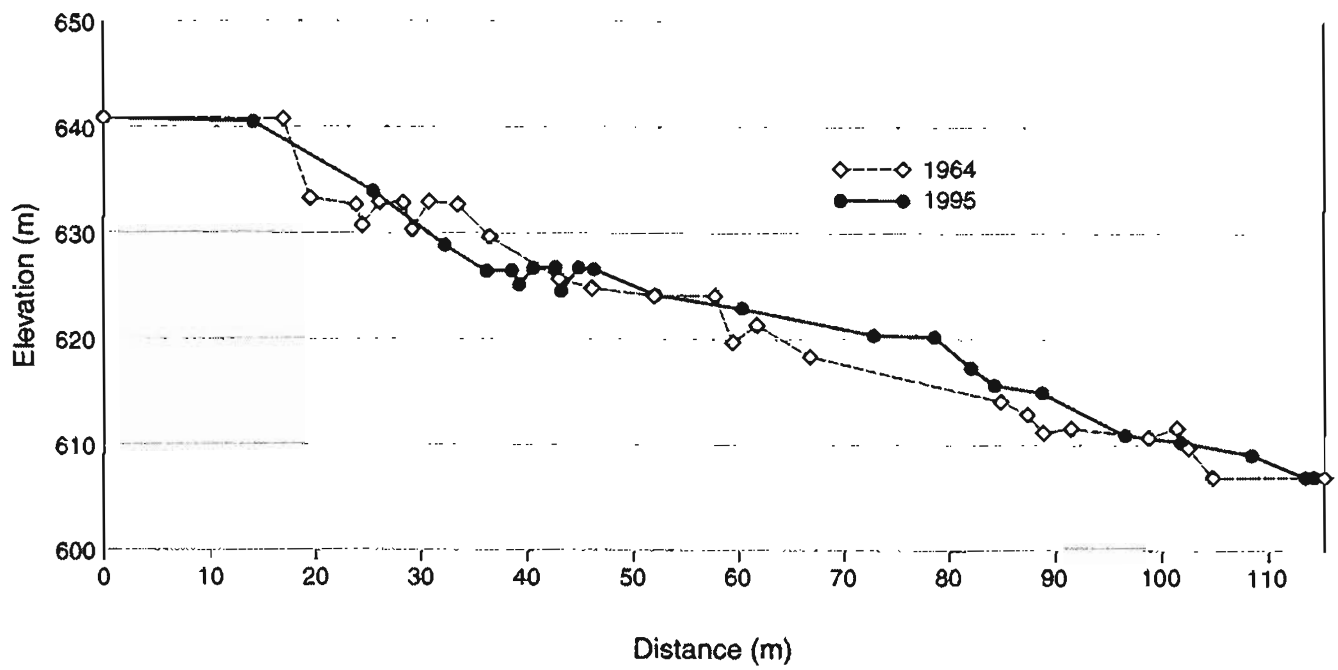


Figure 7. Slope profiles along B-B (Figure 3).
(1) June, 1964. Dashed profile is the approximate pre-slide geometry.
(2) June, 1995. Dashed profile, June 1964.

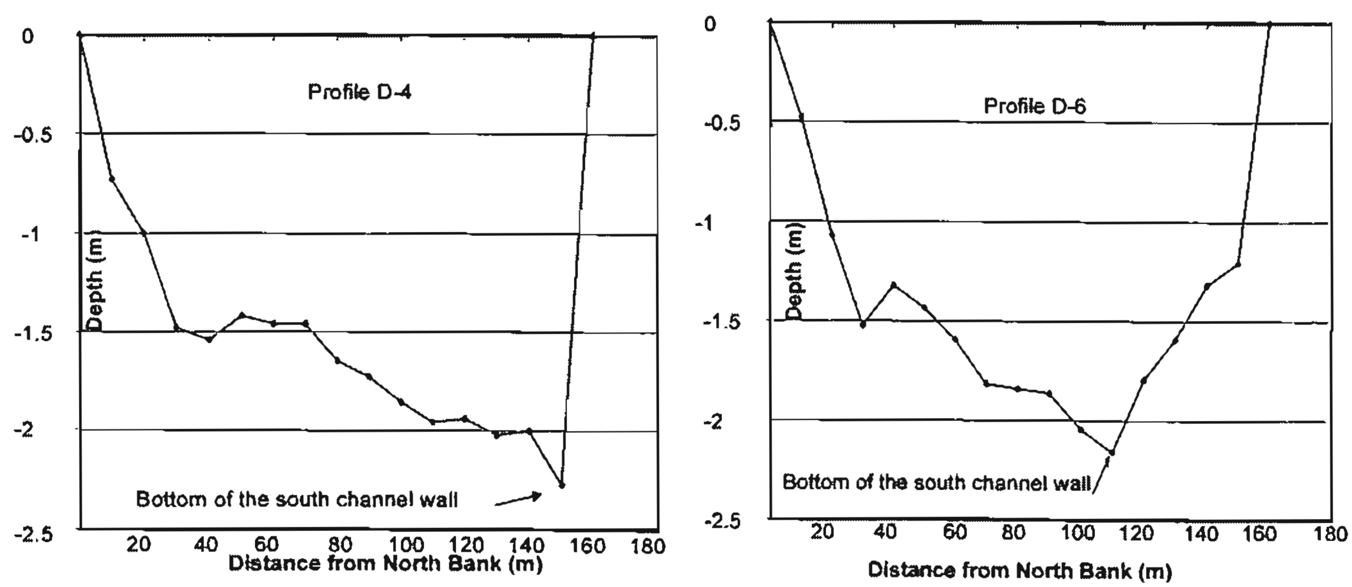


Figure 8. Channel profiles along lines D-4 and D-6 on Figure 6. Vertical exaggeration is 52x.. The south wall of the channel slopes at 13°, the north wall at 3°.

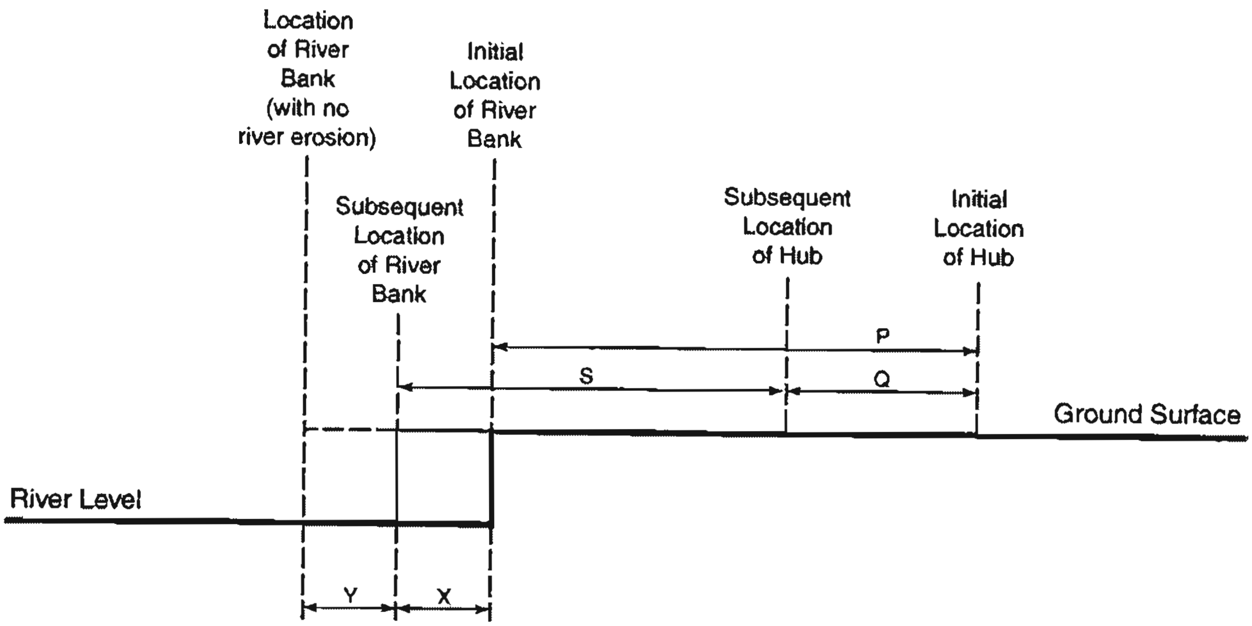


Figure 9. Bank erosion survey parameters

P: Initial distance between hub and the river bank by tape measurement.
Q: Displacement of the hub by control surveying.
S: Subsequent distance between hub and the river bank by tape measurement
Y: River Bank Erosion (P-S)
X: Toe Movement (Q-Y)
if: Q>Y, X>O Toe Advance
Q<Y, X<O Toe Recession