RETROGRESSIVE SLOPE FAILURES
NEAR SASKATOON

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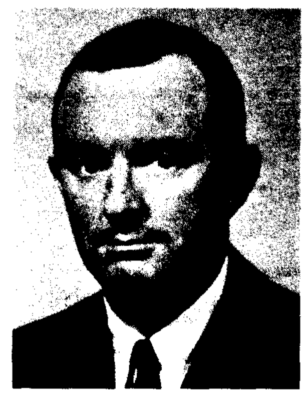
BIOGRAPHY

M.D. Haug was born in Moose Jaw Saskatchewan. He received a diploma in civil engineering technology from the Saskatchewan Technical Institute in 1967 and then joined the Saskatchewan Department of Highways. He worked initially for the Materials and Research Branch, then the Surveys Branch and finally the Geotechnical Branch before joining the staff on the Department of Civil Engineering in 1976. In 1972 he received his Saskatchewan Land Surveyors Commission. In 1974 and 1976 he received his Bachelors degree in civil engineering and his Masters degree in geotechnical engineering respectively from the University of Saskatchewan.

BIOGRAPHY



E. Karl Sauer was born in Regina Saskatchewan. He received his Bachelor of Science in civil engineering in 1952 at Queen's University. After graduation he was employed by the Saskatchewan Department of Highways initially as a Project Engineer, then Division Engineer, then Assistant Design Engineer and finally Senior Geotechnical Engineer. He received his Master of Science degree in geotechnical engineering from Cornell University in 1964 and his Doctor of Engineering in geotechnical engineering from the University of California at Berkeley in 1967. In 1967 he joined the staff of the Department of Civil Engineering at the University of Saskatchewan. Besides teaching and research he is a staff consultant to Ground Engineering Ltd.

BIOGRAPHY

D.G. Fredlund obtained his bachelor of science degree in civil engineering from the University of Saskatchewan, Saskatoon and his master of science degree in 1964 from the University of Alberta, Edmonton. During the summers 1962 and 1963, he worked with the Division of Building Research, National Research Council of Canada, Saskatoon. From 1964 to 1966 he was employed by R.M. Hardy and Associates Limited, Edmonton. In 1966 he accepted a teaching position in civil engineering at the University of Saskatchewan where he remains to the present. From 1970 to 1972 he completed his doctor of philosophy degree at the University of Alberta. In addition to teaching and research, he is a staff consultant to Ground Engineering Limited, Regina. His research has been primarily directed towards the areas of slope stability and the behavior of unsaturated soils.

ABSTRACT

Active landslides are occurring along the banks of the South Saskatchewan River at Saskatoon. A field investigation and stability analysis indicated that multiple retrogressive mechanism is valid in explaining the failures at Beaver Creek, 28 km south of Saskatoon. Computations indicated that lateral pressures ranging from the active to something greater than the at-rest condition tend to support the successive blocks but are not high enough to stabilize the slides. The analysis indicated that the rate of movement of the blocks varies and probably increases downslope.

RETROGRESSION DES CASSURES PRES DE SASKATOON

par: M.D. Haug, E. Karl Sauer et D.G. Fredlund

SOMMAIRE DU CONTENU (traduction professionnelle)

Des glissements de terrain se produisent sur les berges sud de la rivière Saskatchewan à Saskatoon. Une étude sur place ainsi qu'une analyse de stabilité ont démontré qu'un procédé multiple de retrogression explique assez adéquatement les cassures qui se produisent à Beaver Creek, 28 km au sud de Saskatoon. Les calculs entrepris ont démontré que les pressions latérales allant du point actif au point dépassant la condition de repos, tendent réprimer les éboulements consécutifs mais ne sont pas assez fortes pour stabiliser les glissements. L'analyse démontre que le taux de mouvement varie en soit mais qu'il augmente en atteignant le bas de la pente.

RETROGRESSIVE SLOPE FAILURES NEAR SASKATOON

M.D. Haug, E. Karl Sauer, D.G. Fredlund

Introduction

Landslides have occurred and some are presently active along the east bank of the South Saskatchewan River at Saskatoon. The slide area begins at the University of Saskatchewan campus and extends southward approximately 28 km. Pressure has been increasing for residential development along the riverbank (Sauer, 1974). As a result, slope instability in this area is a major concern to public officials and local residents. At the confluence of Beaver Creek with the South Saskatchewan River, landslides are presently active, providing an ideal opportunity to investigate the nature and causes of slope instability in this area (Figure 1).

The Beaver Creek site has several advantages from a research point of view. The area is virgin prairie and therefore provides a natural physical setting free from influences of urban development which would complicate the historical aspects of the study. Furthermore, there exists a large base of data in connection with the history of the river channel, as well as 14 (up to 1975) sets of aerial photographs taken continuously along the river over a period of 30 years. The location of the Beaver Creek site as well as other features in the area can be seen in Figure 2.

Preliminary studies in the area began in 1973. Initially, the geology and groundwater regime were established, followed by a relatively intensive program of test-drilling, mapping, laboratory testing and slope stability analyses. As a result, it appeared that there was enough information available to discuss the slide in sufficient detail to provide a meaningful basis for hypothesizing the causes and mechanisms of failure. It must be recognized, however, that further instrumentation and analysis is desirable to refine the analysis to a greater degree.

Preliminary field observations and survey measurements indicated that, in all probability, the failures at the Beaver Creek site are retrogressive in nature similar to the form described by Skempton and Hutchinson (1969) (Figures 3 and 4).

The retrogressive mechanism has been described by Thomas (1953), Fukola (1953) and Henkel and Skempton (1954). In Canada, Nasmith (1964) investigated a retrogressive slide on the Meikle River in Alberta in overconsolidated clay caused apparently by river downcutting.

Morgenstern and Price (1965) found that the degree and form of disturbance on the surface of a sliding mass can be used as a means for differentiating between circular and non-circular slope movements. The surface deformation at Beaver Creek is of the type found in non-circular, partly translational slides.

Thomson and Hayley (1974) developed a method of analysis for a retrogressive slide on the Little Smokey River. The form of these slides is very similar to the slides at Beaver Creek. As a result, their findings proved to be extremely useful in establishing the mechanism of failure at Beaver Creek.

The Physical Environment at Beaver Creek

The stratigraphy at the site was established from a deep testhole drilled into the Upper Cretaceous clay of the Bearpaw Formation (Figure 5). The interpretation was based on washed drill cuttings, side-hole cores and the electric log. The river level is well above the Upper Cretaceous clays and till-stratified drift contact. As a result, the surficial stratified drift is the most relevant sediment when considering slope stability at this site. However, in order to establish stratigraphic continuity, till was used as the base of exploration in all test holes and piezometer installations.

The surficial stratified drift was deposited during the last continental glacial recession (Christiansen, 1968 and 1971). The topography in the area is such that, as the front of the ice sheet was positioned to the north of the site, it formed topographic closure, creating a proglacial lake. The sediments that were being discharged into this lake were supplied by the North and South Saskatchewan Rivers which were draining the area toward the Rocky Mountains at that time.

Where the rivers emptied into this lake, large deltas were formed, resulting in extensive areas of uniform sands overlying clays and silty clay deposits. This accounts for the stratigraphy at the Beaver Creek site. The uniformity of the sand is indicated by the existence of sand dunes in the area (Figure 3).

Because of the history of sedimentation, including deposition by glacier ice, it is not surprising that the stratigraphy relative to river level is not constant. Thirteen deep testholes along a 28 km section of the river bank confirmed this. This means that the stability situation at Beaver Creek is not necessarily typical of the entire river bank area, even though slides have taken place and some are presently active along the entire section. The geometry of the failures is probably different at any particular location although the sediments have similar properties.

The presence of a fine uniform sand overlying a less permeable clay has resulted in a high water table throughout the area. Even at the edge of the upper scarps of the landslides near the river where significant drawdown would be expected, the water table is only about 7 m from the ground surface.

Mapping

Aerial photographs were flown at a scale of 1:6000 in 1974. In addition, aerial photographs were obtained from the National Air-Photo Library in Ottawa, which were flown at a scale of 1:15840 in 1944. Ground control was established in the area through conventional surveying techniques, thus making it possible to obtain two sets of photogrammetric contours of the slide area separated by a time span of 30 years. Unfortunately, the scales of the two sets of photographs were not the same, resulting in different contour intervals at a map scale of 1:600 were obtained from the 1:6000 scale photographs; four foot controus at a map scale of 1:1200 were obtained from the 1:15840 scale photographs. From these maps it is possible to compare cross-sections and positions of the main scarps and river channel over a significant time period. Stereograms and contour maps are shown in Figures 6, 7, 8 and 9. A control line is shown on both contour maps for purposes of comparison.

The oldest description of the slide area was found in the field notes of the original survey of Part of Township 35, Range 5, West of the Third Initial Meridian, North-West Territories by Henry W. Selby, D.L.S., between October 12 and October 16, 1883. Selby described the right bank in the extending out from shore about 15.00^{c}".* Selby also described the area near the northern extremity of the study area as "heavily timbered flatland banks six to ten feet high which are being washed away every year to allow the trees to fall over into the river". A final quotation taken from the field notes for the area farther north is "high banks with landslides, wooded and full of springs".

The slides at the site extend back from the river approximately 122 m to an elevation approximately 23 m above river level. The average slope is approximately 20 degrees, although the slope in the failed zone is approximately 8 degrees.

A comparison was made of the geomorphology between 1944 and 1974 by orienting the maps according to the control points which are marked on the maps. From the two sets of contour maps it was clear that considerable movement has occurred. Figure 10 shows a comparison of cross-sections of the slide along the control line taken from the two maps. It is apparent that the bank has moved back about 40 m and that the scarp has moved back 37 m, thus establishing an average yearly retrogression of about 1.2 m since 1944. This cross-section indicates that rate of bank and scarp retreat are almost the same at the control line.

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* 15.00^{c} is a measure of distance equal to about 302 m.

The scarp has not eroded as much as the bank north of the control line. One reason for this may be that the scarp is at a higher elevation in this region and perhaps it takes more time for the river to remove the slide debris. The true scarp in this vicinity is difficult to define because there is an area of considerable ground cracking well back from the scarp.

The location of the bank as described by the original river traverse of this portion of the area in 1906 indicates that considerable erosion took place between 1906 and 1974. In addition, the description by Selby indicated that movement was taking placed in 1883. The comparison of scarp locations from the topographic maps is shown in Figure 11. It can be seen that the scarp has moved more in the southwest area between 1944 and 1974, and that the erosion of the bank has been more uniform than scarp retreat over the past 68 years.

Location of the Failure Surface

The failure surfaces of the slide were located by examination of borehole samples in the field. The location of failure surface was indicated by two factors: 1) wet zones with material of very low consistency and 2) zones of high fine sand content. A typical flight auger hole log is shown in Figure 12. These zones were used as indicators because none of the deep testholes were found to contain soft zones

at the depth encountered in the flight auger holes. The electric logs of six testholes in the undisturbed zone did not reveal the fine sand zones other than just below the sand (Figure 13). The origin of the fine sand in these zones is thought to be due to transportation of the fine sand along the failure zone by groundwater and the removal of the clay by suspension in the water. The failure zones in the upper sand layer were not discernable using this method. A summary of the failure zones indicated by the drilling is found in Table 1. It is suggested from this data that there exists a common, near horizontal, failure plane for the slide blocks at 470 m above msl.

The positions of other failure planes were identified by the location of exposed scarps and large cracks in the ground.

Location of the Piezometric Surface

The piezometric surface was established from seven sealed piezometers in the undisturbed area above the scarp and seven open hole test borings in the slide area. About 300 m back from the scarp surface the piezometric surface is at elevation 492 m dropping to elevation 488 m at the scarp and thence down to river level at elevation 475 m. The annual fluctuation (1973 to 1975) is $\pm$ 0.6 m.

River Channel Characteristics

The active slide area is located on the outside bend of a river meander therefore, it is apparent that the river regime is a primary agent in retrogression of the slide, and thus an essential factor to consider in the stability analysis. It was established that the river has shifted as much as 85 m in 68 years and from the stereogram in Figure 2 it appears that it has shifted over an area about 8 km wide at the site since deglaciation 12,000 years ago. A study was made of the rather large amount of quantitative data available on the river channel history. Following the construction of the Gardiner Dam approximately 95 km south of Saskatoon, the river has received yearly surveillance in considerable detail by the Saskatchewan Water Resources Commission (1967).

The data on the river channel indicates that very little if any, channel deepening is taking place at the Beaver Creek site in spite of the fact that the power and spillway facilities at the Gardiner Dam discharge sediment-free water downstream. This is principally because of the distance downstream from the dam and because there is a permanent weir across the river in Saskatoon, 31 km north of the slide area, constructed to maintain a relatively constant minimum water level in the city. The weir represents a base level for the fluvial processes associated with the river.

Consequently, the channel activity at the Beaver Creek site is almost entirely lateral erosion of the bank. Soundings taken across the river at the site confirmed this interpretation.

Slope Stability

Soil Properties

The geotechnical properties of the lacustine sediments at the site are summarized in Figure 14. The samples used to obtain these results were taken from the undisturbed zone back from the upper slide scarp. The material classifies as a medium to highly plastic inorganic clay. The clay size particles ranged from 28 percent to 68 percent, increasing with depth (see electric log Figure 13).

When the preconsolidation pressures are compared to effective overburden stress it appears that the clay immediately below the deltaic sand ranges from slightly to highly overconsolidated with considerable scatter in the results. Preconsolidation is possibly due to desication. The water contents are above the plastic limit which is unusual for clay deposits in Saskatoon. The water contents are below the liquid limit. The clay is fissured with well developed slickensides.

The effective shear strength parameters of the stratified drift are shown in Figure 15. The values shown are for peak and residual conditions. The triaxial test results were used to determine the peak shear strength envelope. The points plotted for peak strength are maximum shear stress for each test and the plotted line represents adjusted values to establish the Mohr envelope. A least squares regression analysis was carried out on the points which established an envelope with a zero intercept and a 25 degree slope. The coefficient of correlation (r^2) was found to be 0.95, indicating an extremely good fit for the points.

Meaningful values of residual strength are difficult to obtain in the triaxial test because of large changes in area of the failure zone at large strains. As a result, direct shear tests were used to estimate the residual strength of the clay. The results of these tests indicate that the Mohr envelope for the material had a cohesion intercept of zero and a slope of 15.4 degrees.

Stability Analysis

Examination of samples during drilling operation, observations of the surface morphology and consideration of cross-section geometry provided strong evidence that a non-circular multiple retrogressive failure mechanism with nearly horizontal common failure plane existed at the Beaver Creek site. A very flat surface slope, the presence of graben block faulting and extensive surface cracking on the sliding blocks were all indications that supported this conclusion.

The nature of a retrogressive mechanism suggests that the slide is triggered by movement or unloading at the toe of the slope. The movement of the slide then works its way up the slope in a series of failures. The simulation of this type of failure requires that the slide be broken into a series of slide blocks. The blocks can then be analyzed to determine their stability. The key to an analysis of this type of failure is understanding or being able to simulate the relationship that exists between the sliding blocks.

Thomson and Hayley (1974) found in a study of a similar slide on the Little Smokey River that the slide moved at a faster horizontal rate the nearer it got to the river. They suggested that leading slideblocks had a small restraining effect on following blocks. A changing rate of horizontal movement seemed logical at Beaver Creek as well because the vertical dimensions of the sliding blocks appear to decrease toward the river even though the rate of retrogression at the scarp is approximately equal to the lateral transgression of the river. Material must travel faster in the shallow part of the slide to maintain a volume balance. A graphical illustration of how the different portions of the slide travel at different speeds, and end up with configurations similar to those described in the slide, is shown in Figure 16. The movements are indicated by vector arrows and a volume balance is maintained in the slide at all times.

In the analysis of the slides, the leading block was considered to be moving faster than the next block, providing it had a factor of safety less than one. Inherent in this assumption is that the leading block does not provide a horizontal restraint to movement of the following block. However, the portion of the first block which is above the slip surface of the second block must be assumed to contribute a normal force on the second block.

Residual shear strength values were used to analyze the block at the toe of the slide because the block is moving. The results indicated that the lower block of the slide is unstable having a factor of safety against sliding of 0.78. Following blocks were then analyzed with the assumption described above and all were found to have factors of safety less than one (Figure 17).

When the slide was analyzed as a single sliding block along the same horizontal failure zone using residual shear strength parameters, the factor of safety was found to 1.82. Therefore, the hypothesis of a retrogressive mechanism appears valid.

The safety factors appear to be low considering the slow rate of lateral movement. This suggests that the lateral support of adjacent downslope sliding block is significant. Consequently, an analysis was performed (Figure 18) to establish the equivalent fluid lateral pressure required to produce a factor of safety of 1.0. The results are shown in Table II.

The lateral pressure for the at rest condition was calculated to be 800 kg/m^3. The average lateral pressure shown in Table II is 721 kg/m^3. The lowest equivalent fluid pressure is 320 kg/m^2 which is approximately equal to the active condition, whereas two of the slide blocks required lateral pressures higher than the at rest condition to produce a factor of safety of 1.0. The variation in equivalent fluid pressure would be consistent with the relative movements of the blocks.

The peak shear strength parameters were used to compute the first time failure of the undisturbed material above the upper scarp. A slip circle starting about 25 m from the present scarp had a factor of safety of 1.0. All circles back from this were greater than 1.0, whereas all circles forward toward the upper scarp were less than 1.0.

Conclusions

The results of this analysis showed that the multiple retrogressive mechanism is valid in explaining the slope failures at Beaver Creek. It also demonstrates that the increase in rate of horizontal movement toward the river described by Thomson and Hayley (loc.cit) as a significant factor in the stability analysis.

According to the analysis, the downslope sliding block provides some lateral support to the block above it. The pressures required to produce a factor of safety of 1.0 range from the active to something above the at rest condition. The variability of these lateral pressures tends to support the assumption that the blocks are moving at different rates.

The failures at Beaver Creek are not necessarily typical of the entire river bank south of Saskatoon. It was found that the geology of the bank changes progressively northward which is reflected by the geomorphology of the river flood plain. Therefore, at any given site along the riverbank the geology and present day river regime must be considered for that site. On the other hand, a valuable insight was gained into the soil properties in the area and a mechanism of failure.

ACKNOWLEDGEMENTS

Funds for this project were supplies by the National Research Council and the Saskatchewan Research Council. The Saskatchewan Department of Highways contributed significantly to the test drilling and sampling program. Dr. E.A. Christiansen supervised the geological investigation and was responsible for the interpretation of the geology of the area.

TABLE I

ELEVATION OF FAILURE ZONES

OBSERVED FROM TEST BORINGS

TABLE II

EQUIVALENT FLUID PRESSURES

ACTING AS A RESTRAINT

ON THE SLIDING BLOCKS

TABLE I ELEVATION OF FAILURE ZONES

OBSERVED FROM TEST BORINGS

Hole No.	Elevation	
	Feet	Metres
1	1573 - 1575	479.57 - 480.18
1	1563 - 1565	476.52 - 477.13
2	1551 - 1553	472.87 - 473.48
2	1542	470.12
3	1572 - 1578	478.27 - 481.10
3	1542	470.12
4	1580 - 1581	481.71 - 482.01
4	1573	479.57
4	1555	474.09
4	1540 - 1542	469.51 - 470.12

TABLE II

Block No.	Kg/m^3
1	
2	1233
3	320
4	464
5	593
6	609
7	561
8	769
9	1217

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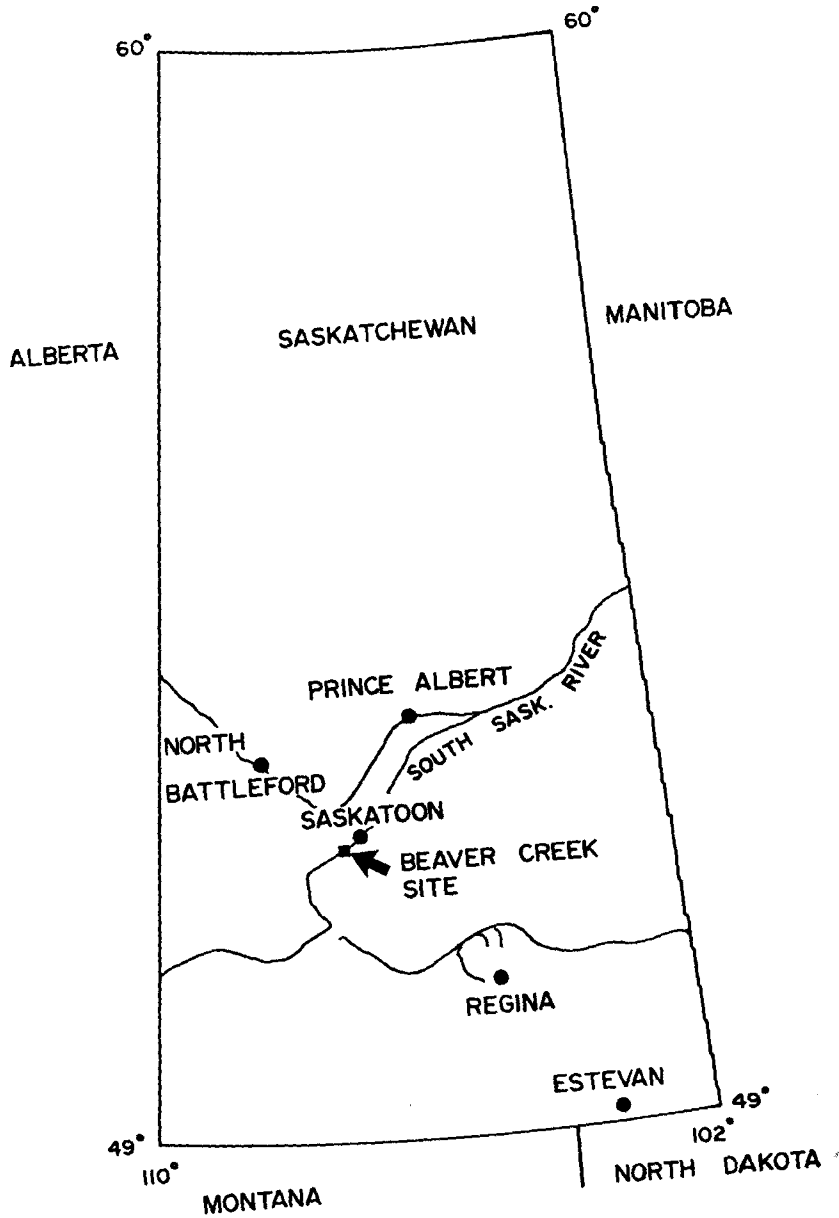
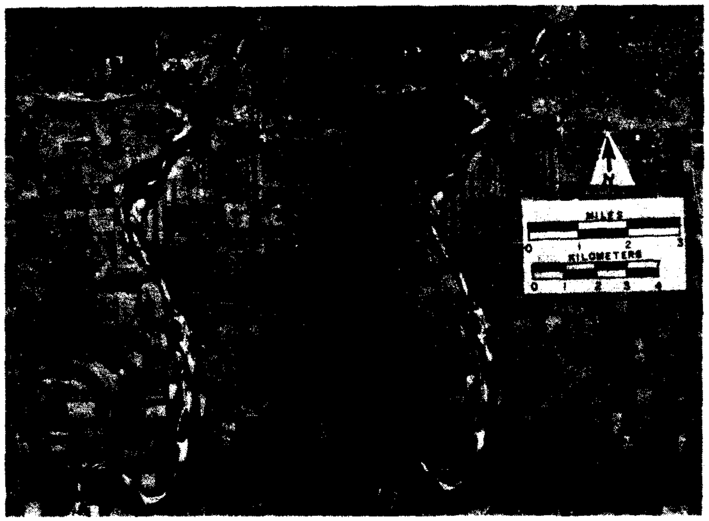
Figure 15	Shear strength parameters
Figure 16	The retrogressive mechanism used in the stability analysis
Figure 17	Cross-section of slide blocks showing factors of safety assuming no lateral restraint
Figure 18	Equivalent fluid pressure acting as lateral restrain on each slide block

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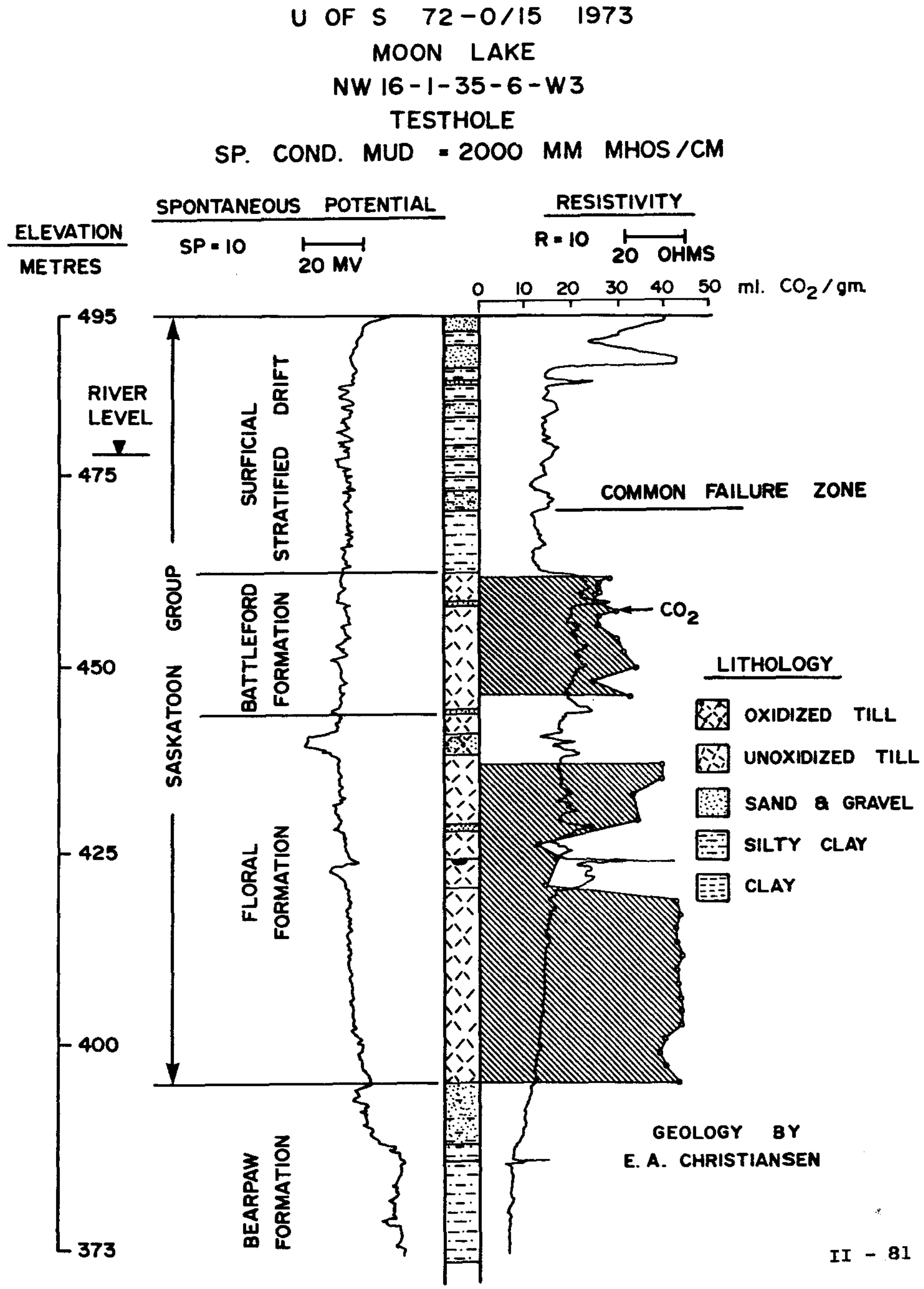

U OF S 72-0/15 1973
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TESTHOLE
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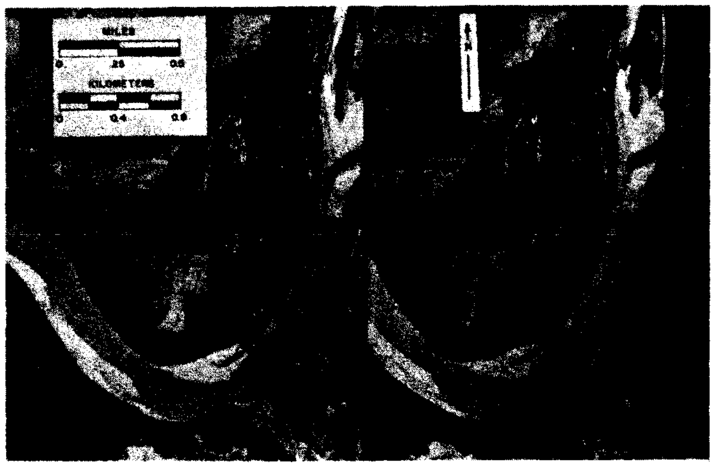
ELEVATION
METRES
SPONTANEOUS POTENTIAL
SP = 10
20 MV
RESISTIVITY
R = 10
20 OHMS
0 10 20 30 40 50 ml. CO_2/gm.
495
475
450
425
400
373
RIVER LEVEL
SURFICIAL STRATIFIED DRIFT
SASKATOON GROUP
BATTLEFORD FORMATION
FLORAL FORMATION
BEARPAW FORMATION
COMMON FAILURE ZONE
CO_2
LITHOLOGY
OXIDIZED TILL
UNOXIDIZED TILL
SAND & GRAVEL
SILTY CLAY
CLAY
GEOLOGY BY
E. A. CHRISTIANSEN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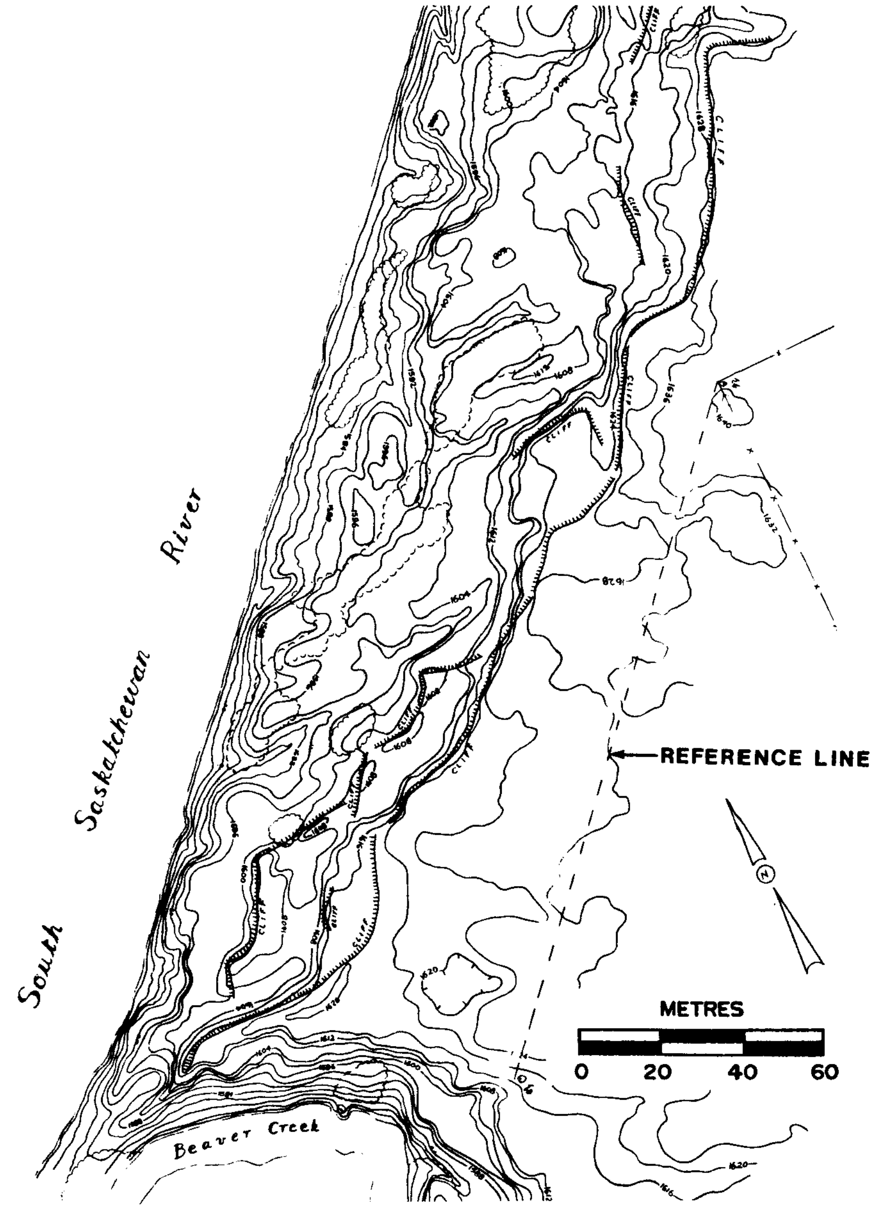
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Beaver Creek
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REFERENCE LINE
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METRES
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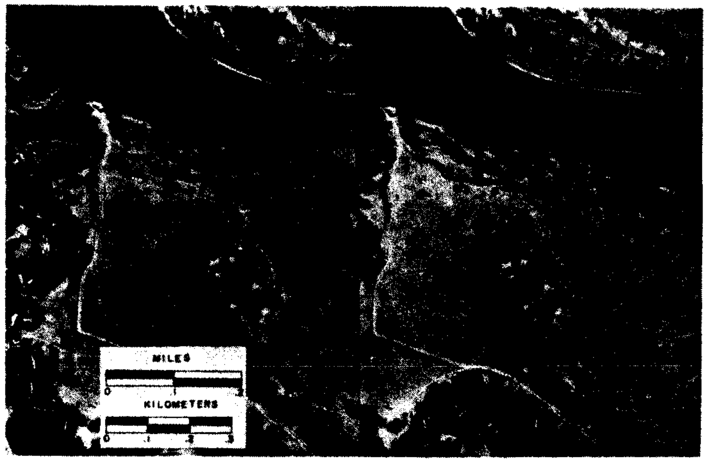
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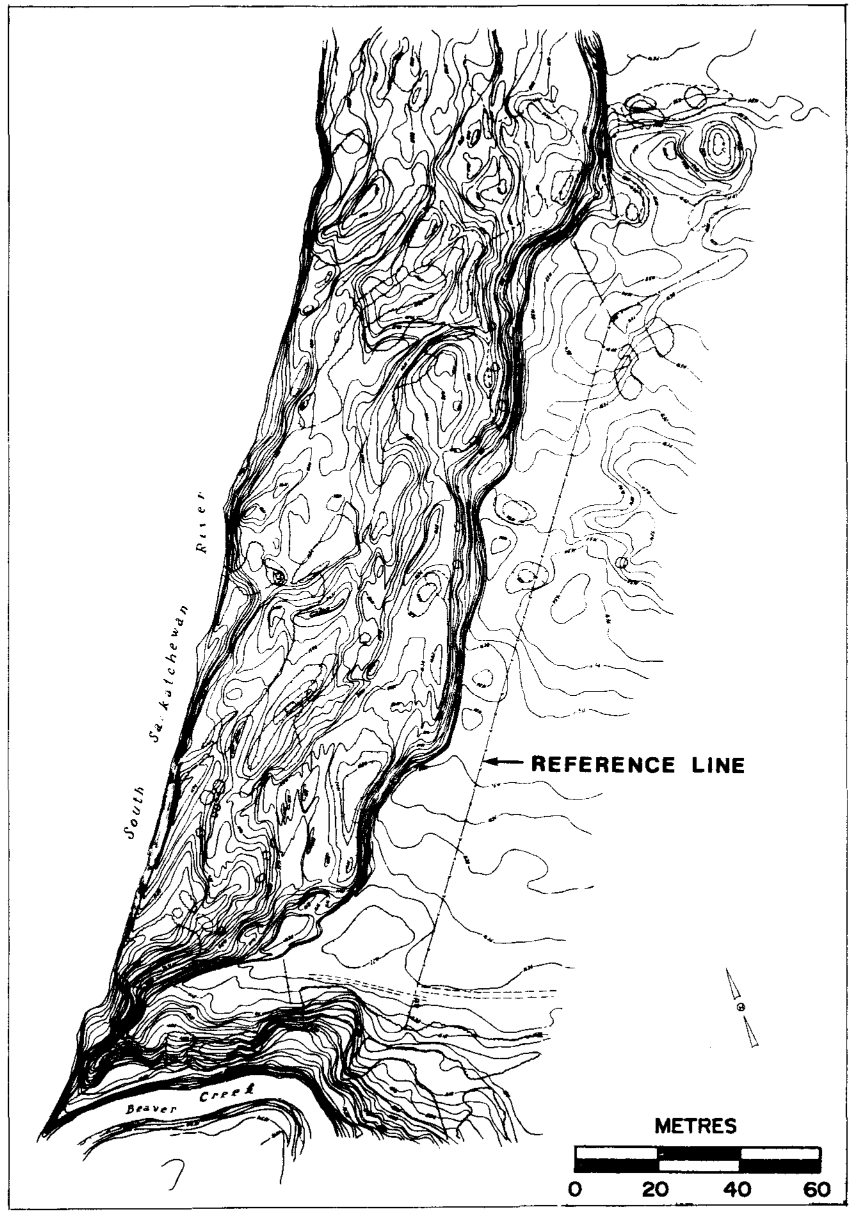
South Sa. katchewan River
Beaver Creek
REFERENCE LINE
METRES
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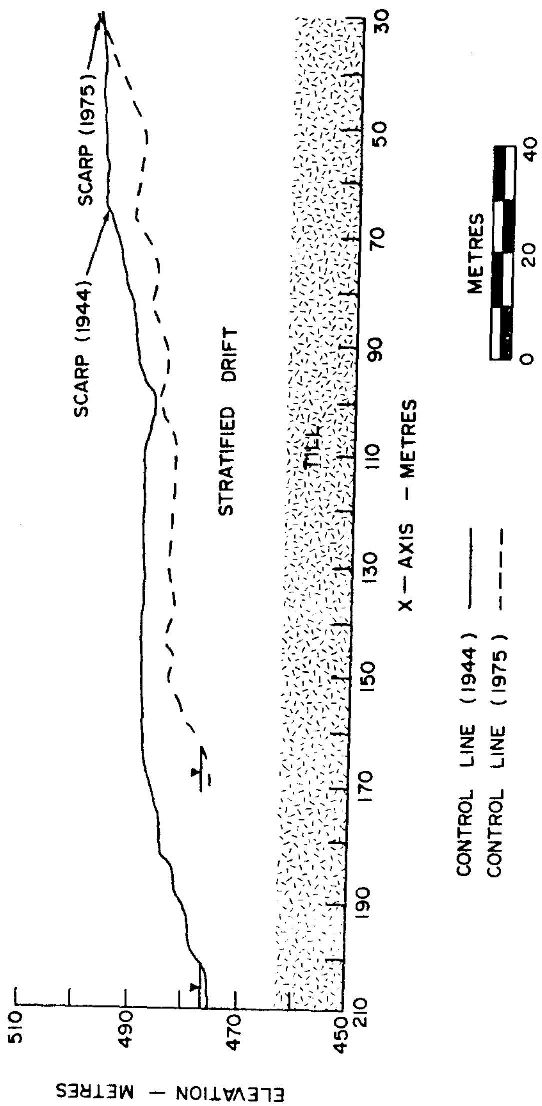
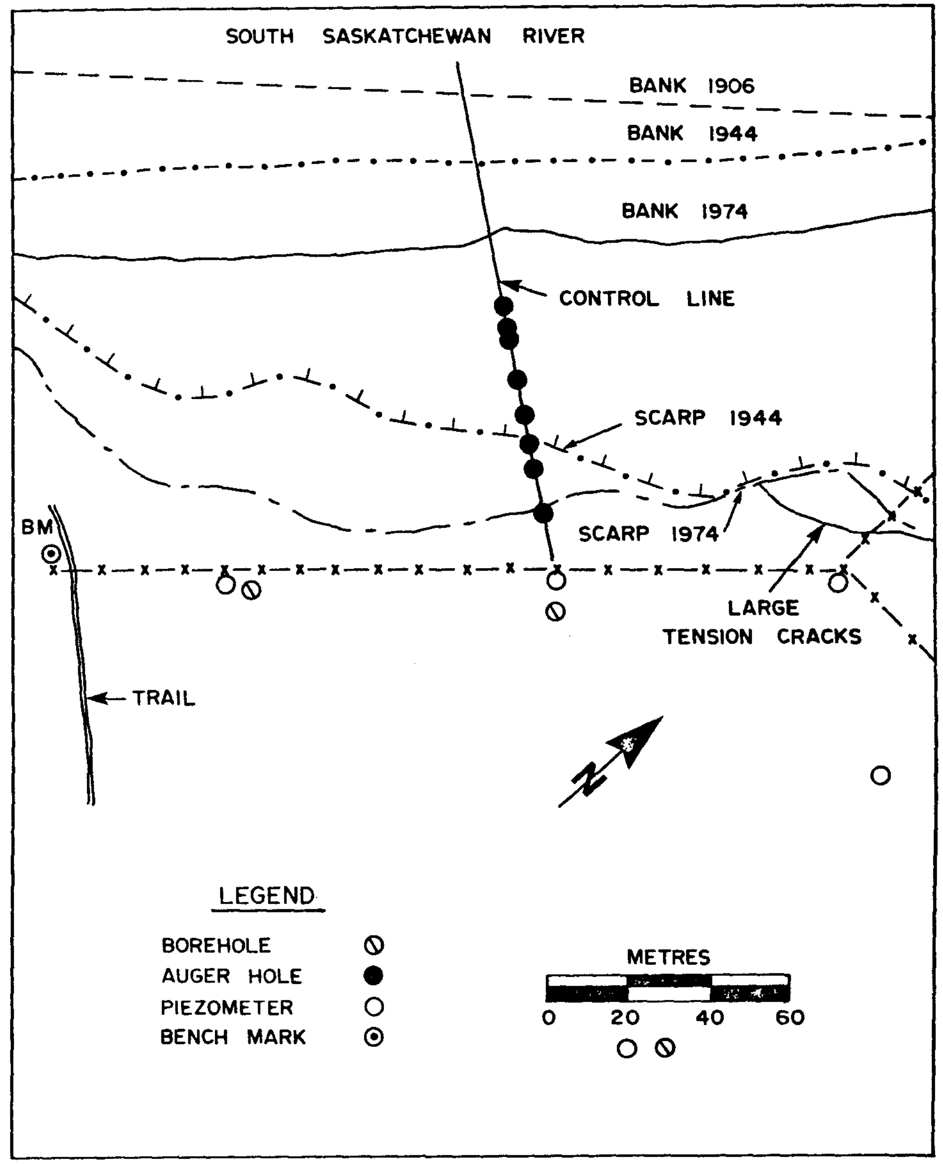

SCARP (1975)
SCARP (1944)
STRATIFIED DRIFT
TILL
X — AXIS — METRES
30
50
70
90
110
130
150
170
190
210
METRES
0
20
40
CONTROL LINE (1944)
CONTROL LINE (1975)
510
490
470
450
ELEVATION — METRES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BANK 1906
BANK 1944
BANK 1974
CONTROL LINE
SCARP 1944
SCARP 1974
BM
LARGE
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LEGEND
BOREHOLE
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METRES
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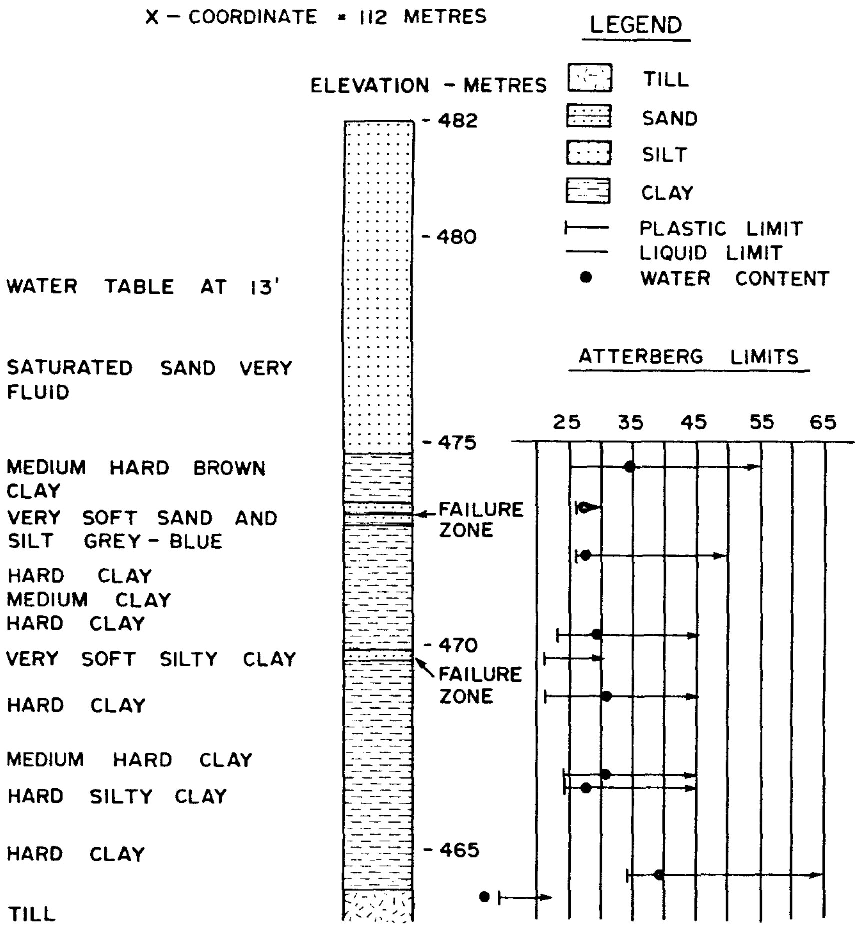
20
40
60


X - COORDINATE = 112 METRES
LEGEND
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SAND
SILT
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PLASTIC LIMIT
LIQUID LIMIT
WATER CONTENT
ELEVATION - METRES
482
480
475
470
465
WATER TABLE AT 13'
SATURATED SAND VERY FLUID
MEDIUM HARD BROWN CLAY
VERY SOFT SAND AND SILT GREY - BLUE
FAILURE ZONE
HARD CLAY
MEDIUM CLAY
HARD CLAY
VERY SOFT SILTY CLAY
FAILURE ZONE
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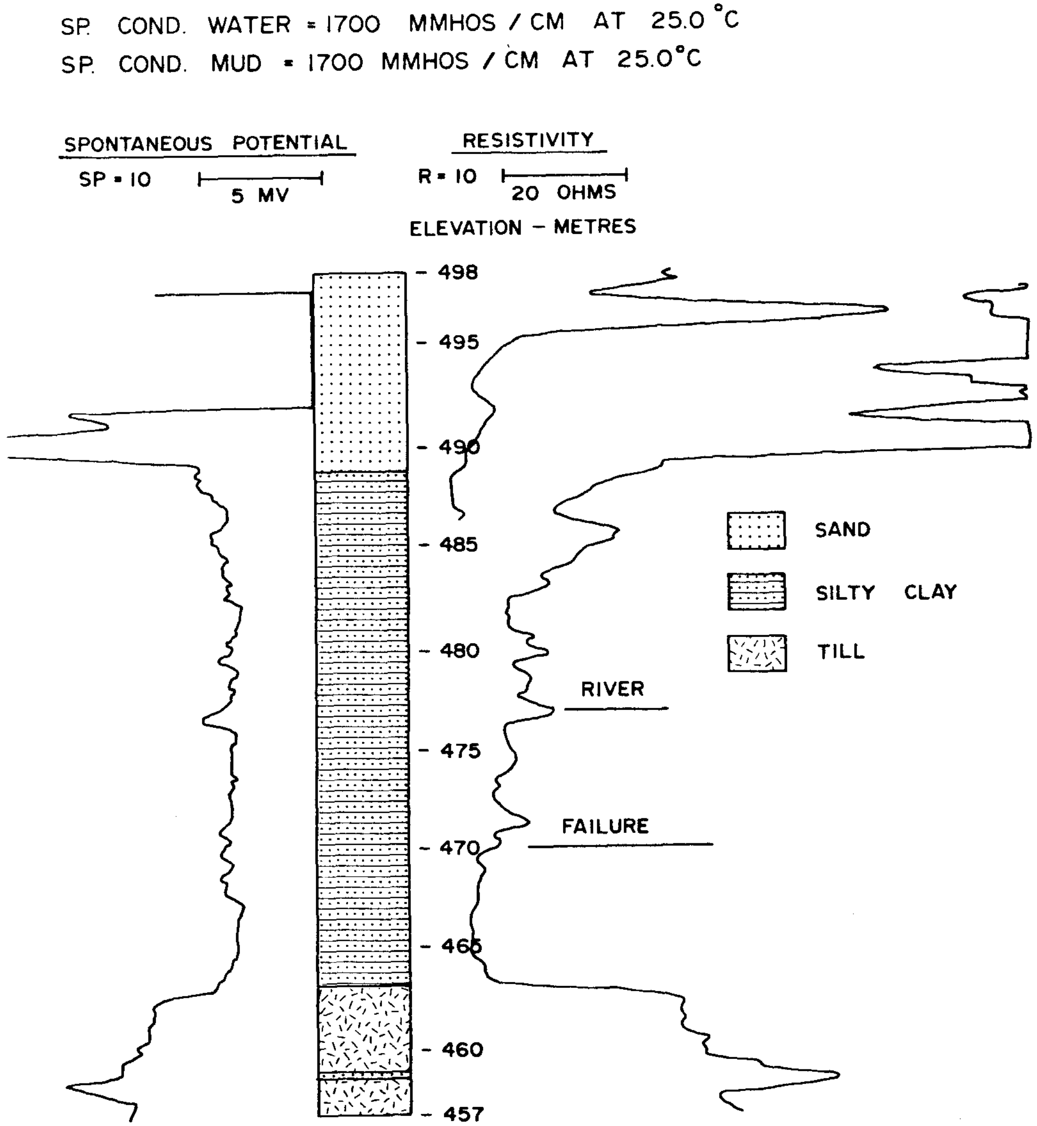
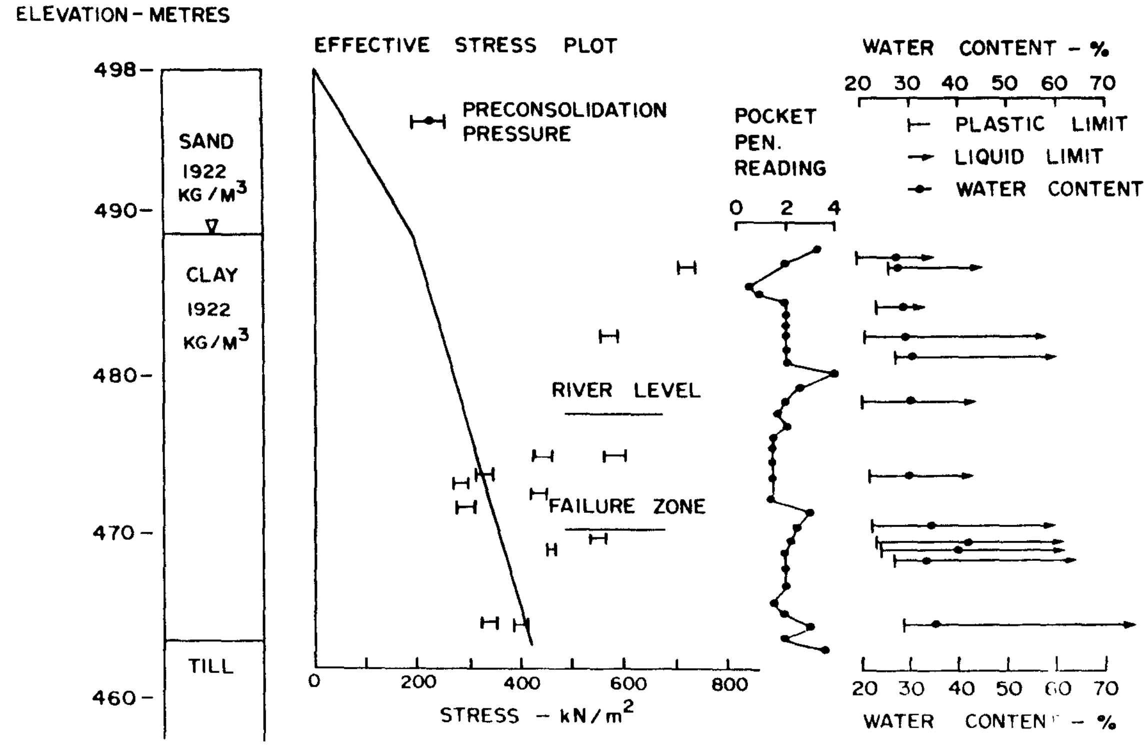
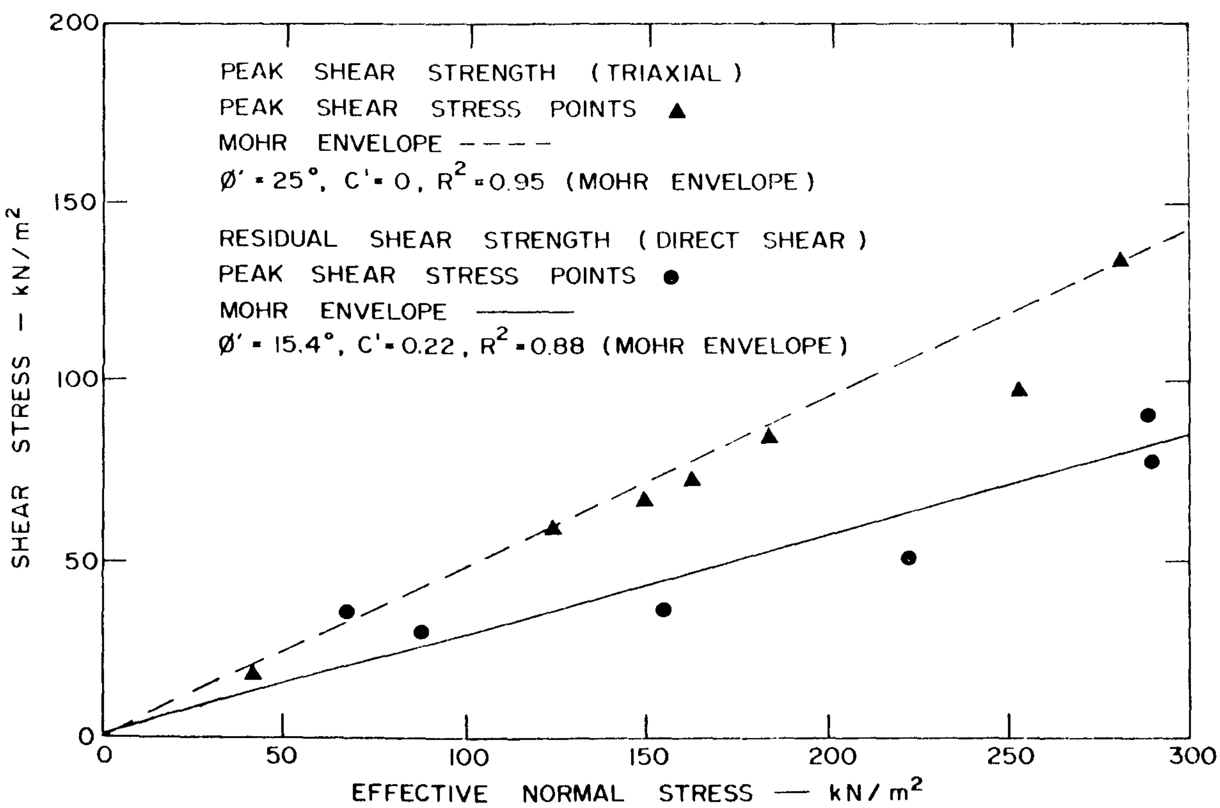
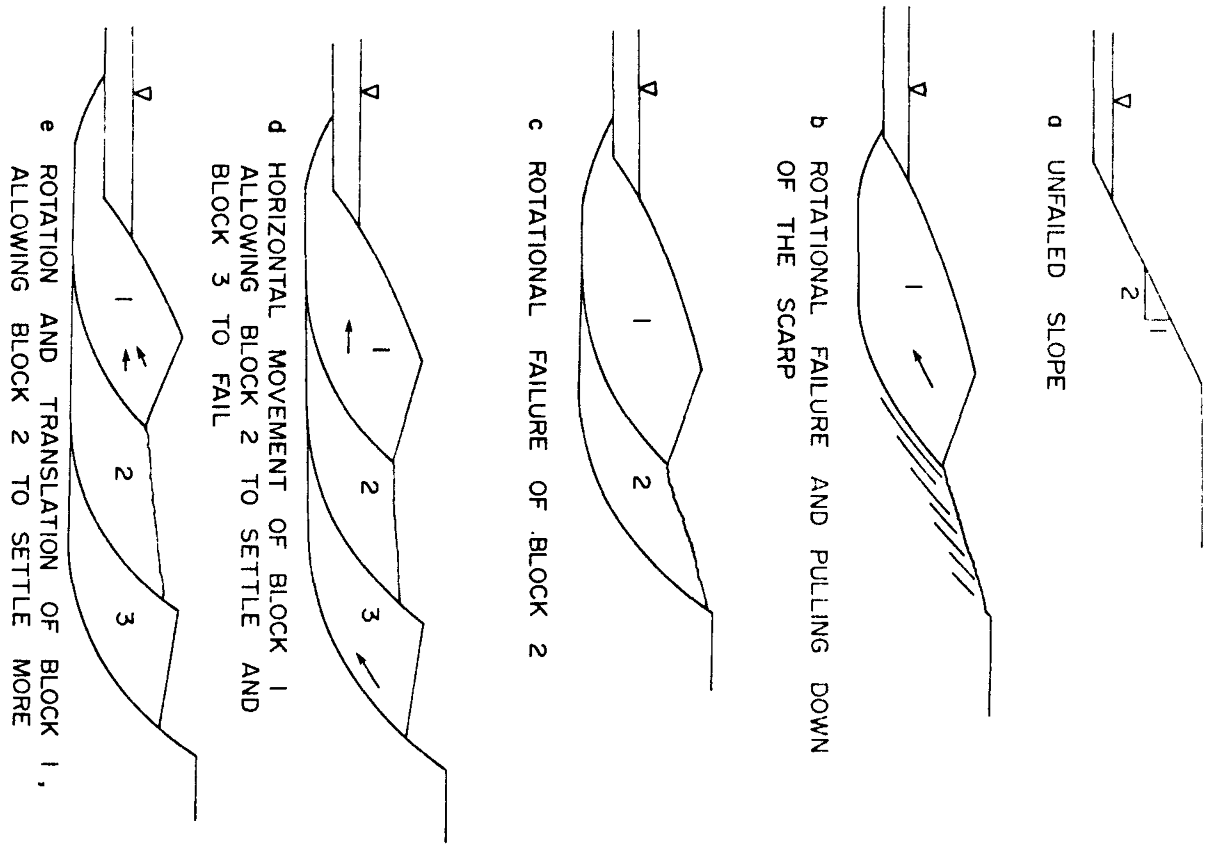
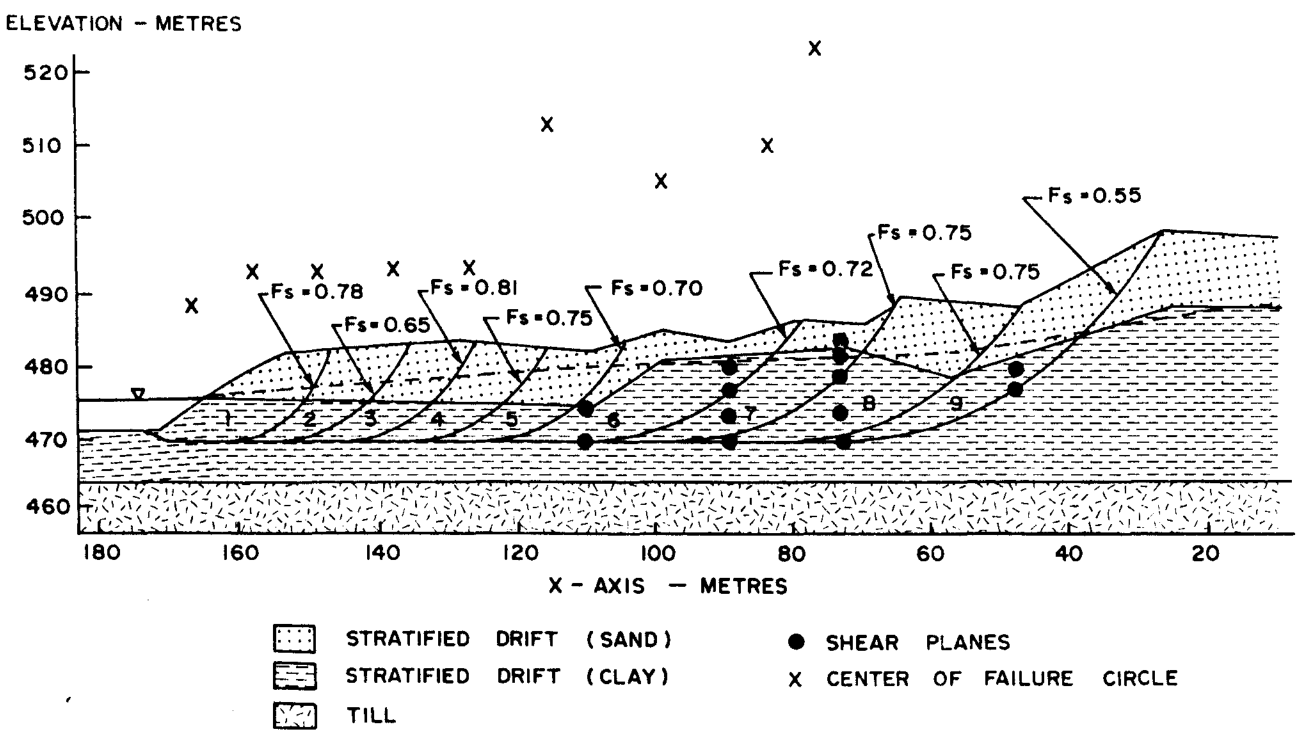
TILL
ATTERBERG LIMITS
25 35 45 55 65

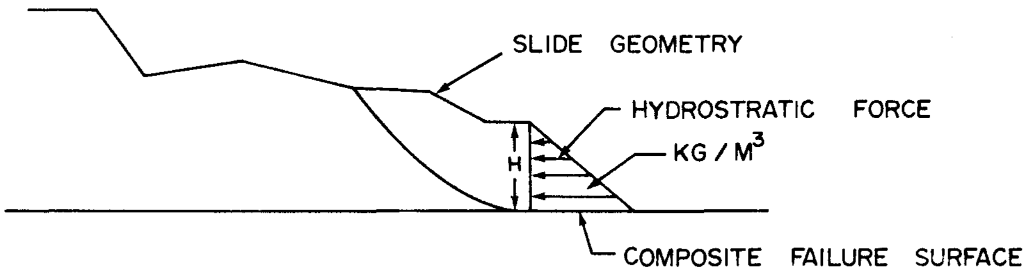

SP. COND. WATER = 1700 MMHOS / CM AT 25.0 °C
SP. COND. MUD = 1700 MMHOS / CM AT 25.0°C
SPONTANEOUS POTENTIAL
SP = 10
5 MV
RESISTIVITY
R = 10
20 OHMS
ELEVATION - METRES
498
495
490
485
480
475
470
465
460
457
SAND
SILTY CLAY
TILL
RIVER
FAILURE


ELEVATION - METRES
498
490
480
470
460
SAND
1922 KG / M3
CLAY
1922 KG/M3
TILL
EFFECTIVE STRESS PLOT
PRECONSOLIDATION PRESSURE
RIVER LEVEL
FAILURE ZONE
0 200 400 600 800
STRESS - kN/m2
POCKET PEN. READING
0 2 4
WATER CONTENT - %
20 30 40 50 60 70
PLASTIC LIMIT
LIQUID LIMIT
WATER CONTENT


PEAK SHEAR STRENGTH (TRIAXIAL)
PEAK SHEAR STRESS POINTS ▲
MOHR ENVELOPE - - - -
Ø' = 25°, C' = 0, R2 = 0.95 (MOHR ENVELOPE)
RESIDUAL SHEAR STRENGTH (DIRECT SHEAR)
PEAK SHEAR STRESS POINTS ●
MOHR ENVELOPE ———
Ø' = 15.4°, C' = 0.22, R2 = 0.88 (MOHR ENVELOPE)
SHEAR STRESS - kN/m2
0 50 100 150 200
0 50 100 150 200 250 300
EFFECTIVE NORMAL STRESS — kN/m2


a UNFAILED SLOPE
b ROTATIONAL FAILURE AND PULLING DOWN OF THE SCARP
c ROTATIONAL FAILURE OF BLOCK 2
d HORIZONTAL MOVEMENT OF BLOCK 1 ALLOWING BLOCK 2 TO SETTLE AND BLOCK 3 TO FAIL
e ROTATION AND TRANSLATION OF BLOCK 1, ALLOWING BLOCK 2 TO SETTLE MORE


ELEVATION - METRES
520
510
500
490
480
470
460
Fs = 0.55
Fs = 0.75
Fs = 0.72
Fs = 0.75
Fs = 0.78
Fs = 0.81
Fs = 0.70
Fs = 0.65
Fs = 0.75
1
2
3
4
5
6
7
8
9
180
160
140
120
100
80
60
40
20
X - AXIS - METRES
STRATIFIED DRIFT (SAND)
STRATIFIED DRIFT (CLAY)
TILL
SHEAR PLANES
X CENTER OF FAILURE CIRCLE


SLIDE GEOMETRY
HYDROSTRATIC FORCE
KG / M3
H
COMPOSITE FAILURE SURFACE