THE UNIVERSITY OF MANITOBA

SLOPE STABILITY CONSIDERATIONS
OF A
RIVERBANK IN METROPOLITAN WINNIPEG

by

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A THESIS

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ABSTRACT

Pneumatic piezometers and slope indicators were installed, in a riverbank along the Red River in Metropolitan Winnipeg, to monitor porewater pressures and possible riverbank movements. The instrumented riverbank had failed previously and was later partly stabilized. The performance of the pneumatic piezometers was successful as they were capable of rapidly measuring the porewater pressures developed in the relatively impervious Lake Agassiz Clay. Piezometric conditions were determined for the period November 1968 to May 1969, inclusive.

The porewater pressure data indicated that the major component of the hydraulic gradient was in a downward direction. The most critical piezometric condition in terms of slope stability was not determined as the time of measurement was too short. The two slope indicators presented data which indicated that the riverbank was in a slow state of movement. The slope indicator data also indicated that a major portion of the slip zone was immediately above the clay-till interface, and that the movement of the riverbank was predominantly in a lateral direction. The best approximation of the shape of the slip surface was found to be that defined by the sliding block analysis.

Employing effective "residual" shear strength parameters for the soils within the slip zone, slope stability analyses were conducted by the Fellenius, Simplified Bishop's and Janbu Methods. The Janbu method was considered to be the superior method of analysis because its non-circular slip surface feature enabled the theoretical slip surface to have a geometry very similar to the observed slip surface.

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LIST OF SYMBOLS

α = angle between base of slice and horizontal,

α_t = angle between interslice force and horizontal,

b = slice width,

c' = cohesion in terms of effective stress,

c'_R = residual cohesion in terms of effective stress,

d = depth or height of slice,

F = the Factor of Safety for the stability of the slope.

The definition of the Factor of Safety is as follows:

$$F = \frac{\text{available shear strength}}{\text{shear strength required for equilibrium}} .$$

γ_t = total unit weight of a material.

H_n = horizontal interslice force,

H_{n+1} = horizontal interslice force,

L = length of base of slice

P = total reaction normal to the base of the slice,

P' = effective reaction normal to the base of the slice,

ϕ' = angle of shearing resistance in terms of effective stress

$\phi'_{available}$ = angle of shearing resistance in terms of effective stress which is available on the vertical side of the slice,

ϕ'_R = angle of shearing resistance in terms of effective stress,

$\phi'_{req'd}$ = angle of shearing resistance in terms of effective stress which is required on the vertical side of the slice,

S_m = mobilized shear force,

U = porewater pressure,

u = unit porewater pressure,

LIST OF SYMBOLS

V_n = vertical interslice force,

V_{n+1} = vertical interslice force,

W = total weight of the slice.

SLOPE STABILITY CONSIDERATIONS
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CHAPTER I

INTRODUCTION

1.1 OBJECTIVES

Pneumatic piezometers were installed in a riverbank along the Red River in Metropolitan Winnipeg to monitor porewater pressures. This type of instrumentation had not previously been used on riverbanks in the Winnipeg area. Therefore a prime objective was to evaluate the installation techniques and actual performance of this instrument in the local riverbank soils.

It was known that a slip surface or slip zone existed within the riverbank because the riverbank had failed previously and was later partly stabilized. Therefore further objectives were to determine more accurately the location and geometry of the slip surface, and to determine the rate of riverbank movement, if in fact it was presently in a state of movement. The determination of these latter objectives were aided by two "slope indicator" installations.

The porewater pressure data obtained was limited to the period November 1968 to May 1969, inclusive, and therefore possible porewater pressure conditions are only partly represented. The continuation of obtaining data was a part of another investigation.

In order to utilize the porewater pressure data obtained, computer programs were developed based on the Fellenius[1], Bishop's

Simplified[2], and Janbu[3] methods of slope stability analysis. The results obtained from each of these slope stability analyses were compared with field failure conditions to determine which method was most applicable.

1.2 PREVIOUS INVESTIGATIONS

The subject of the slope stability of the riverbanks of the Metropolitan Winnipeg area has received considerable consideration and study due to their relatively unstable characteristics. These riverbanks generally consist of plastic clays of Glacial Lake Agassiz, which are generally underlain by glacial till.

MISHTAK[4] in a 1960 survey reported that very few banks along the Red and Assiniboine Rivers were stable. He found only six stable slopes of the 141 slopes examined along the riverbanks. The unstable slopes had visible tension cracks, sloughing or toe erosion. They either had suffered failures in the last two years or were in the state of creep. The failure mechanisms appeared to be relatively complex as indicated by the fact that the shear strength of the clays in those slopes tended to reduce with time (Ref. 4). BARACOS[5] found that toe erosion on the concave portions of the river caused a gradual deterioration in the long term stability of these riverbanks. Factors such as surface drainage, internal porewater pressures, and the "rapid drawdown" of the rivers have also contributed to these instabilities.

The predominant soil profile common to the Red River Valley has previously been described by MACDONALD[6], RIDDELL[7], and BARACOS[5]. Basically the soil profile consists of an upper layer of brown clay, occasionally an intermediate layer of a brown and grey clay, and an underlying generally somewhat siltier grey layer known as "blue" clay. These glacial lake clays are generally covered by a layer of more recent siltier and organic deposits ranging in thickness from two to sixteen feet. Table 1, compiled by BARACOS[5] is a list of the depth of occurrence of these clays and some of their pertinent properties. Note that where these clays occurred in riverbanks they generally showed some considerable disturbance and lower unconfined strengths. A further list of properties and shear strength parameters of these silts and clays is presented in Table 2. It was compiled by SUTHERLAND[8] from tests conducted at the University of Glasgow on samples extracted from the Winnipeg Floodway site.

The analysis employed to determine stability of these slopes has generally been the classical "Fellenius Method of Slices" with a circular slip surface assumption. The total stress ($\phi = 0$) analysis has been used extensively, but appeared to be successful only when used with lower shear strength values than those determined from unconfined compression tests. BARACOS[5] and MISHTAK[4] found that the unconfined compressive strength of these clays averaged about 2000 lbs./sq. ft., but when this value was applied to a failed slope a safety factor greater than unity usually resulted. In 1950, A. BARACOS reported to the Greater Winnipeg Dyking Board that he found that the calculated factor of safety for slopes in the Winnipeg Clays was over-estimated. He indicated that it would be more realistic to use a value of 800 to 1200 lbs./sq. ft. for the unconfined compressive strength. SUTHERLAND[9] also recommended the application of a reduced value of shear strength when using the $\phi = 0$ analysis.

This apparent discrepancy between analytical and observed

TABLE 1

Some Properties of Greater Winnipeg Glacial Lake Clays

(From BARACOS, Ref. 5)

	Brown "Chocolate" Clay				Mixed Brown and Grey Clay				Grey "Blue" Clay			
	Max.	Av.	Min.	No. of Tests	Max.	Av.	Min.	No. of Tests	Max.	Av.	Min.	No. of Tests
Depth to top of stratum - ft.	16	11	2	147	28	20	6	176	35	25	15	154
Depth to bottom of stratum - ft.	40	25	11	147	35	25	8	176	62	45	15	154
Moisture content - %	57	48	27	76	63	56	31	57	61	41	27	44
Dry Density - lb/cu/ft.	99	77	64	73	87	69	53	51	102	79	63	39
Moist density - lb/cu/ft.	125	109	95	83	114	108	98	51	130	112	101	42
Saturation - %	100	97	86	73	100	98	89	50	100	98	89	32
Unconfined Compression Strength - lb/sq/ft.	4570	2054	865	87	3790	2169	112	49	3570	2182	1188	44
Plastic Limit	40	30	14	36	36	31	26	9	32	25	16	17
Liquid Limit	117	89	37	36	110	93	70	9	95	76	37	17
Plasticity index	88	59	23	36	75	63	51	9	68	50	20	17

TABLE II

Recent Test Results of Winnipeg Glacial Lake Clays

(From SUTHERLAND, Ref. 8)

Material	Depth	Water Content			Liquid Limit	Plastic Limit	Wet Density	Preconsol. Pressure	Residual Strength Angle	Peak Shear Strength Parameters				
		Avg.	Range	No. Obs.						Stress Range	Bulk Clay		On Laminations	
	ft.	%			%	%	p.c.f.				c' p.s.i	Ø'	c' p.s.i.	Ø'
Tan Silt	12	34.4	29-38	44	53	22	120	4 to 5 tsf	25	20 - 70 psi	4.2	24½	--	--
								60-80 psi		3 - 20 psi	1.6	31	--	--
										0 - 3 psi	0.8	40	--	--
										0 - 12 psi	---	--	0.4	32
										12 - 70 psi	---	--	4.5	17
Brown Clay	10	54.9	44-61	60	120	34	105	4.1-4.8 tsf	8	Complete	5.8	20.1	--	--
								60-70 psi		Complete	---	---	0.5	15
Grey Clay	25.5	45.9	40-59	83	72	25	111	2.7-3.6 tsf	10	Complete	2.0	23½	--	--
								42-56 psi		Complete	---	---	0	26½
Grey Plastic Clay	29.5	62.7	43-81	116	101	32	103	0.7 tsf	11	Complete	1.4	17.7	--	--
								11 psi		Below 10 psi	0.4	27.1	--	--
										Above 10 psi	1.7	17.3	--	--
										Complete	---	---	0.7	16

stability behaviors has generated study on possible alternative methods that should be employed to analyse the stability of a riverbank in the Red River Valley. Both BARACOS[5] and SUTHERLAND[9] have suggested that the effective stress method of analysis might provide a better correlation between analytical behavior and field performance for Winnipeg Clays.

CHAPTER 2

INVESTIGATION

2.1 ORGANIZATION OF INVESTIGATION

The steps that were undertaken in this investigation were as follows:

1. A riverbank with the following characteristics was selected:
    a) One that was potentially in danger of a slope failure, such that the installed instrumentation would monitor the activities preceding and during the anticipated failure.
    b) Riverbank site was to be readily accessible by equipment to assist the installation of required instrumentation and to obtain subsequent data.
2. A site survey was conducted to obtain a typical profile of the ground surface.
3. An extensive sub-surface investigation was conducted to determine and classify the soils of the bank, determine depth to a firm foundation material, depth of water table, and to extract a series of undisturbed samples of various soils for soil classification and laboratory shear strength determinations.
4. The following instruments were installed:
    a) A series of pneumatic piezometers, and
    b) two "slope indicators".

5. A continuous record of river levels were kept.
6. The following parameters were selected for each soil in order to conduct a slope stability analysis:
    a) Total unit weight, and
    b) Shear strength parameters.

2.2 SITE:

The riverbank under investigation is located on the Red River in the City of St. Vital within Metropolitan Winnipeg. A typical cross-section is shown in Figure 1. This riverbank is on the outside edge (concave side) of the river and therefore has been subjected to the higher velocity currents that generally prevail in these areas. Two characteristics of the site then follow:

1. It is not in a zone of river deposition and therefore the insitu soils are primarily of a glacial lake origin (lacustrine).
2. Its stability in the past was threatened by toe erosion both from river currents and Spring ice flows.

As indicated by Figure 1, the slope of the bank is relatively gentle, approximately 7 to 1. The whole section is virtually void of tree growth except for a narrow dense stand of willows along the river edge immediately North of the indicated cross-section. Therefore for the greater part the only existing vegetation is grass which extends to the river edge. Some rip-rap exists at the river edge but is not continuous. It consists of a random array of boulders and old concrete slabs ranging in size from approximately 1 to 3 ft. in diameter. Further up the slope there exists some buried rip-rap consisting of the previously mentioned

CROSS-SECTION OF RIVERBANK

at

ST. VITAL SITE

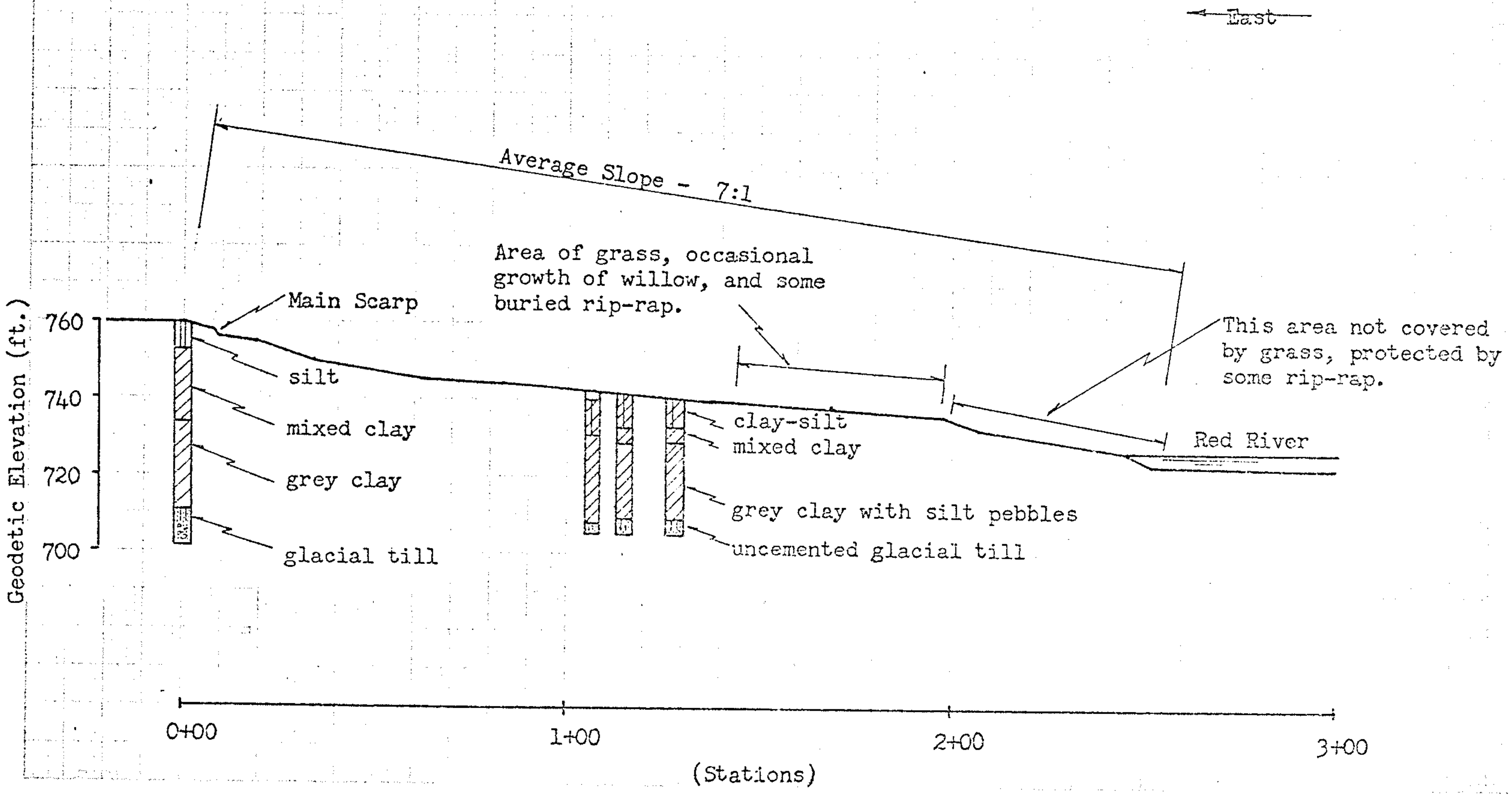


Figure 1

concrete slabs and boulders. Due to the sparce vegetation it is apparent that this rip-rap tends to retard toe-erosion during the period of Spring break-up when high water levels, currents of high velocity and movements of large blocks of ice greatly increase the potential forces of erosion.

The riverbank is a typical example of an unstable bank that has failed in the past and is now moving at a very slow rate. To stabilize this riverbank, the following measures were undertaken:

1. To provide rip-rap at the toe of the slope. Its main function was to provide resistance against erosion by the forces of river currents and ice flows. The large size of the rip-rap is important as the relatively heavy weights of the individual slabs have accounted for the partial success in resisting soil displacement by the erosion forces.
2. The steepness of the slope was reduced. The relatively gentle slope of 7:1 would normally be adequate.
3. To provide continuous grass vegetation on the slope. This measure facilitated surface water drainage and therefore minimized the quantity of water that would flow into the subsoil either by seepage or via tension cracks.

But since the time of the above mentioned stabilization measures, the slope has resumed its movement toward the river. Deterioration in stability is visibly evident as a significant scarp exists at Station 0 + 09 where an abrupt vertical drop of approximately 2 to 3 ft. exists in the ground surface profile. Further down the slope there are several ground surface cracks which run almost parallel to the main scarp. These might indicate the possibility of independent block movements within the slope.

2.3 SOIL PROFILE:

The predominate soil type of this riverbank is a highly plastic varved clay of glacial Lake Agassiz. Figure 2 illustrates several borehole soil logs as determined from the soil investigation conducted at the site. The 6 to 12 inches of topsoil consists of a highly organic material which supports the vegetative growth on the slope. Underlying the topsoil are three distinct clay layers which are readily identified by color. The upper clay layer is a light brown clay which extends to a depth of approximately 6 to 10 feet. The intermediate clay layer is a mixed brown and grey clay which ranges in thickness from approximately four feet at the bottom of the slope to almost 20 feet at the top. The bottom layer is a grey clay with numerous pebble-size silt inclusions. This clay layer rests on an almost horizontal bed of non-cemented glacial till, and has a maximum layer thickness of nearly 25 feet. These clays are classified as "CH" soils according to the Unified Classification system. They are highly plastic clays with plasticity index in the 50 to 60 percent range and wet densities of approximately 110 pounds per cubic foot.

The upper five feet of the underlying non-cemented glacial till consists predominately of a mixture of fine sand and silt with increasing content of coarser sand and pebbles with depth. The till was very dense as indicated by the penetration refusal of the sampling shelby tubes.

Existing at a depth near the bottom of the boreholes, although not actually determined in this investigation, is a carbonate rock known as the "Red River Formation" composed of dolomitic limestone and dolomite. Auger refusal at 5 to 8 foot depths into the till could be attributed either to a cemented glacial till or the limestone bedrock. According to

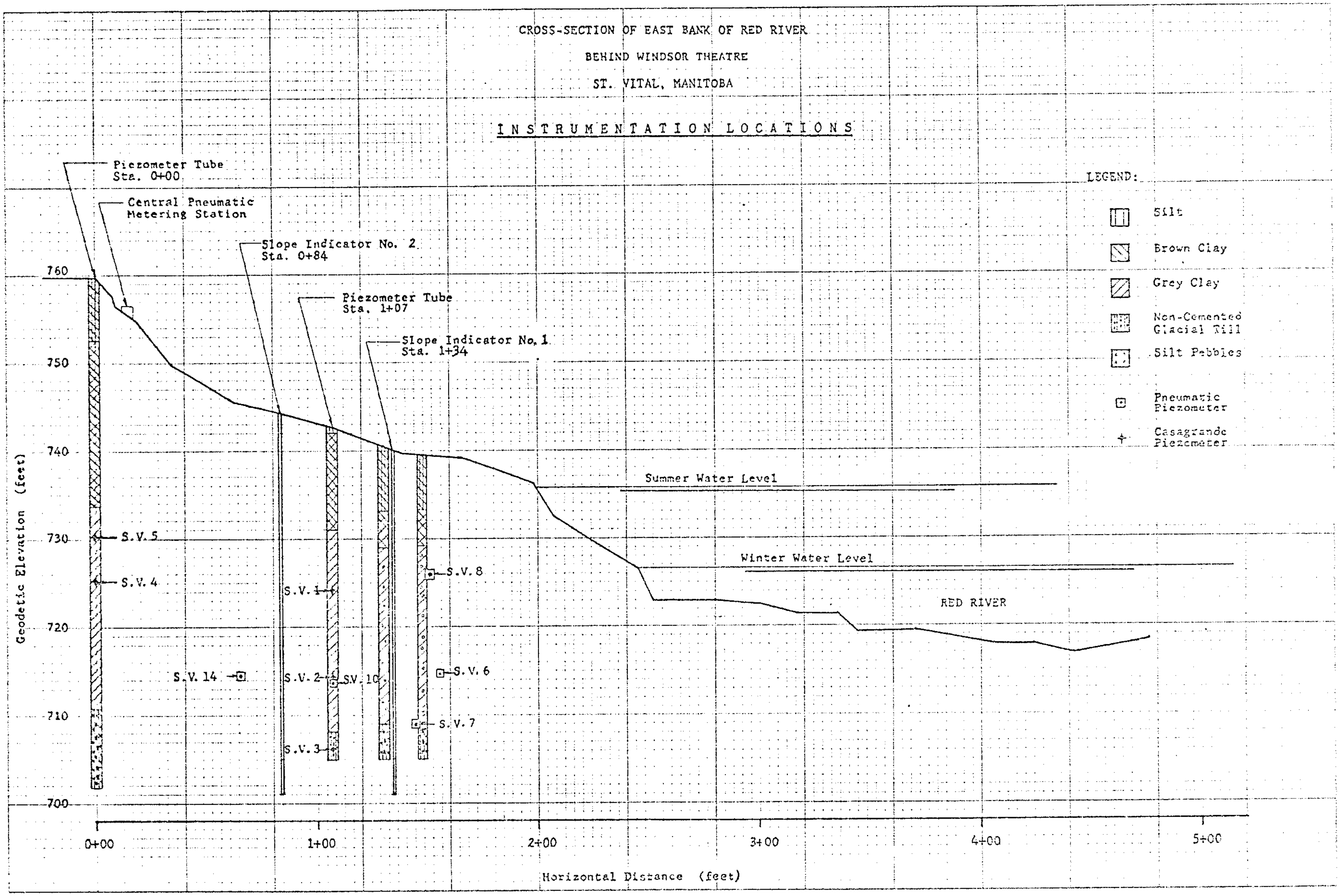

CROSS-SECTION OF EAST BANK OF RED RIVER
BEHIND WINDSOR THEATRE
ST. VITAL, MANITOBA
INSTRUMENTATION LOCATIONS
Piezometer Tube Sta. 0+00
Central Pneumatic Metering Station
Slope Indicator No. 2 Sta. 0+84
Piezometer Tube Sta. 1+07
Slope Indicator No. 1 Sta. 1+34
LEGEND:
Silt
Brown Clay
Grey Clay
Non-Cemented Glacial Till
Silt Pebbles
Pneumatic Piezometer
Casagrande Piezometer
Summer Water Level
Winter Water Level
RED RIVER
S.V. 5
S.V. 4
S.V. 1
S.V. 14
S.V. 2
SV. 10
S.V. 3
S.V. 8
S.V. 6
S.V. 7
760
750
740
730
720
710
700
Geodetic Elevation (feet)
0+00
1+00
2+00
3+00
4+00
5+00
Horizontal Distance (feet)

Figure 2

the topographic plan of the Bedrock Surface by RENDER,[10] bedrock in this particular area is in the vicinity of 700 foot elevation (Geodetic), which was the approximate elevation of the auger refusals.

CHAPTER 3

INSTRUMENTATION

3.1 PIEZOMETERS

The St. Vital site had been previously instrumented by the Manitoba Water Resources Branch with five "Casagrande" type piezometers. Initial examination indicated that these piezometers were insufficient in number, and possibly were too slow to respond to porewater pressure changes. To overcome these shortcomings, five pneumatic piezometers were installed in the autumn of 1968. These piezometers were placed at various positions on a cross-section perpendicular to the river and at various depths as indicated by Figure 2.

The pneumatic type of piezometer employed at the St. Vital site operates by measuring the air pressure required to close a hydra-pneumatic balance system. The main body of the unit is constructed of polyethlene, the main working parts are a belofram of dacron, Buna N. Springs of silicone bronze with baked teflon coating, and a neoprene O-ring. The tubing for the lines from the instrument to the terminal is constructed from heavy wall nylon enclosed in polyvinyl chloride. The two leads at the read-out terminal are easily connected to the control unit by quick couplings.

Figure 3 is a schematic diagram of the piezometer tip. The unit has a stiff diaphragm which is slightly displaced upward due to the pressure of the porewater. In order to measure the magnitude of the porewater pressure, air pressure from the pressure cylinder in the control unit is applied through Line 2A. During the pressure build-up, the air pressure flows from the control unit via Line 2A past the O-ring seal. The flow of air continues up Line 2 back up to the second lead of the control unit. The returning air pressure is recorded on a pressure gauge mounted on the control unit. When the supply air pressure equals the porewater pressure the diaphragm is displaced downward, closing the O-ring check. This closure creates a seal which precludes further flow of air into Line 2. The air pressure in Line 2 at closure is then equal to the porewater pressure and is recorded on the pressure gauge. The minute movement required to close the O-ring check causes a slight displacement of water. According to the manufacturer a 1/16 inch line,which is open to the atmosphere, allows this minute displacement of water to occur without movement of water into or out of the soil.

The pneumatic piezometric units were calibrated by the manufacturer prior to delivery in accordance to the required length of lead for each unit. These units were re-calibrated at the University of Manitoba prior to installation by directly connecting the units to variable air pressure lines incorporating sensitive air gauges. The calibration curves of the piezometers are shown in Figures 23 and 24 of Appendix "B" and were employed to correct all data monitored at the site. The calibration process indicated that great errors in readings resulted if the rate of air flow into Line2A was not regulated carefully. The input air supply valve had to be adjusted in such a manner as to allow a minimum rate of air pressure build-up. This technique prevented an air pressure build-up lag in Line 2 and therefore precluded readings which were less than actual.

The installation of these units was simplified by employing piezometers encased in well-points connected to one-inch pipe. The units were then driven into the soil either by a hammer or hydraulic force. Standard 1 inch water pipe sections were added until the required depth was reached.

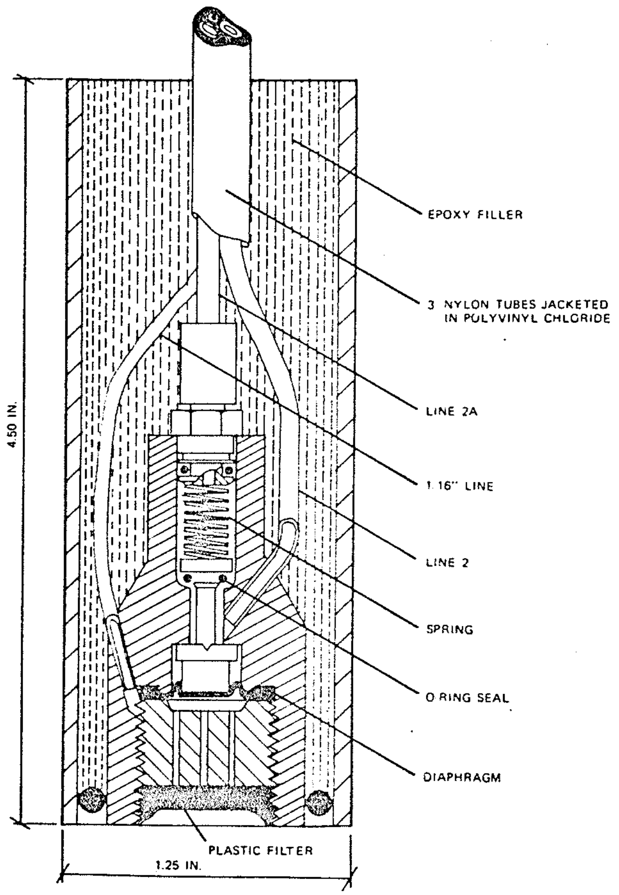


Figure 3: Schematic Diagram of the Piezometer Tip

The installation procedure was generally as follows:

1) A 4 inch diameter hole was advanced by means of flight augers, truck mounted drill, to within 10 feet of final desired depth of piezometer.
2) A well-point encased piezometer with adequate length of 1 inch water pipe was then positioned at the bottom of the hole.
3) Sufficient water was poured into the hole to completely submerge the well point.
4) The first piezometer installed was driven to the desired depth by allowing a 40 pound hammer to drop in a free fall of several feet unto the afore-mentioned pipe. A special adapter was connected to the pipe to guide the manual lifting and free fall of the hammer. For the subsequent installations the well-point was forced to the desired depth by employing the hydraulic pressure exerted by the drill truck.
5) The tubing from the piezometer unit extended vertically to within two to three feet from the ground surface, then traversed underground at a three foot depth parallel to ground surface to the Central Pneumatic Metering Station.
6) In an effort to assure that the unit would be sealed from the surface and overlying soil layers, multiple coats of fibre glass were applied to the 4 foot pipe section immediately above the unit. The fibre glass layers provided a pipe diameter slightly larger than the leading well-point unit and also furnished a rough shaped surface to create a tight pipe-soil contact.

The features of this unit that made it appealing for installation at this site are as follows:

1. The negligible time lag in developing the actual pore water pressure reading is mandatory for the relatively impervious insitu clays (coefficient of permeability is in the order of 10^{-9} to 10^{-11} cm/sec)[5] existing at the site.
2. Clay soil corrosion is eliminated by the non-metallic construction of the underground portions of the unit.
3. Two features inherent of the air system are: (1) elimination of the freezing of lines, and (2) allowance for the lines to be terminated at a single point to facilitate the collection of readings.
4. A convenient measuring procedure as facilitated by the ease of operation and movement of the light-weight portable control case.
5. Relative ease of installation as attained by employing piezometers encased in well-points.

Refer to Appendix "C" for a documentation on various types of piezometers that are presently being employed. Brief discussions are given of the operation, advantages, and limitations of each type of piezometer system.

3.2 SLOPE INDICATORS:

Slope Indicators were installed along the profile, as indicated by Figure 2, one at Station 0 + 84 and the other at Station 1 + 34. The instrument employed was the Series 200-B unit supplied by the Slope Indicator Co. of Seattle, Washington.

The instrument is lowered down an aluminum casing which has four equispaced longitudinal grooves, the grooves controlling the orientation of the instrument in the casing. The inclination of the instrument at any depth in the casing is determined by means of a pendulum activated electrical circuit. The actual value of the inclination is obtained from Wheatstone Bridge readings at the ground surface. The detailed operation of this instrument is presented in the "Instruction Manual" issued by the manufacturer. Inclination readings are taken at frequent intervals of depth and are subsequently converted to displacements. Consecutive readings at the same depth intervals at periodic intervals of time are used to determine depth and rate of ground movement. The instrument has a sensitivity of one part in 1000, which means that a tilt of as little as three minutes of arc can be detected. This corresponds to a lateral displacement of one inch in 100 feet of depth.

Aluminum casing was installed at the two locations as indicated above. The 3.18 inch outside diameter casings were lowered into holes drilled by flight augers. The casings were anchored into the firm till layer. The void on the outside of the casing was then backfilled with an expansive grout near the base of the hole, and with a sand from just above the base to the ground surface.

CHAPTER 4

OBSERVATIONS AND FIELD MEASUREMENTS

4.1 THE RED RIVER

Some of the important features of the Red River affecting the stability of its riverbanks have been cited by BARACOS[5] and are herein summarized as follows:

1. The Red River has cut a sinuous path within a relatively straight belt of approximately one mile width within the Metro Winnipeg area.

2. The terrain is relatively flat except where the riverbanks drop 30 to 50 feet to the river bed.

3. Depth of the river has been limited by the underlying firm glacial till or bedrock.

4. River velocities are generally low except in time of flooding when peak velocities range between 5 to 6 feet per second.

5. The river is subject to spring flooding with changes in level of over 30 feet occurring during major floods and frequently up to 18 feet.

Drawdown following spring peak river levels is not immediate, ranging from two to six weeks. Normal winter level of the river is at a Geodetic elevation of approximately 727 feet. The river has risen from 15 to more than 30 feet above normal winter level during Spring flooding. But since the construction of the Red River Flood Control Structure in 1969 it is not likely that the 30 foot level will be reached again. During the summer, the river level ranges from 6 to 8 feet above normal winter level as controlled by the locks located at Lockport, downstream from Winnipeg. This level is maintained throughout the summer, and then late in the Autumn the river is allowed to drop to its normal winter level.

4.2 GEOHYDROLOGY:

The geohydrology of this same area is thoroughly documented by RENDER.[10] This reference refers to a major aquifer underlying the Winnipeg area, known as the Upper Carbonate aquifer which occurs in the top fifty to one hundred feet of the Paleozoic limestones and dolomites and is confined above by the glacial drift. It is of interest to determine the effect this aquifer has on the piezometric regime of the riverbanks. The upper 25 feet of the carbonate rock of this aquifer is characterized by a network of fractures, joints, and bedding planes which provides the permeability to make it the zone of most water flow. The lower portion of the overlying glacial drift consists of boulder till and associated glaciofluvial deposits which are generally cemented.

The recharge of the Upper Carbonate aquifer occurs in three main segments:

1. From the east by infiltration in the glacial till upland east of the lacustrine plain and in the Birds Hill aquifer complex.
2. From the north-west via areas of thin glacial till.
3. From the south-west through a thin veneer of glacial till and fluvial deposits.

Several observation wells, located in the general area of the St. Vital Riverbank Test Site, are seated in the Upper Carbonate Aquifer and have recorded piezometric levels up to 735 feet (Geodetic Elevation). As the bedrock surface elevation at the test site is approximately 700 feet it is possible that the piezometric pressures of this aquifer supplements the effect of the river and groundwater seepage in the clay zones to create the piezometric regime of the riverbank.

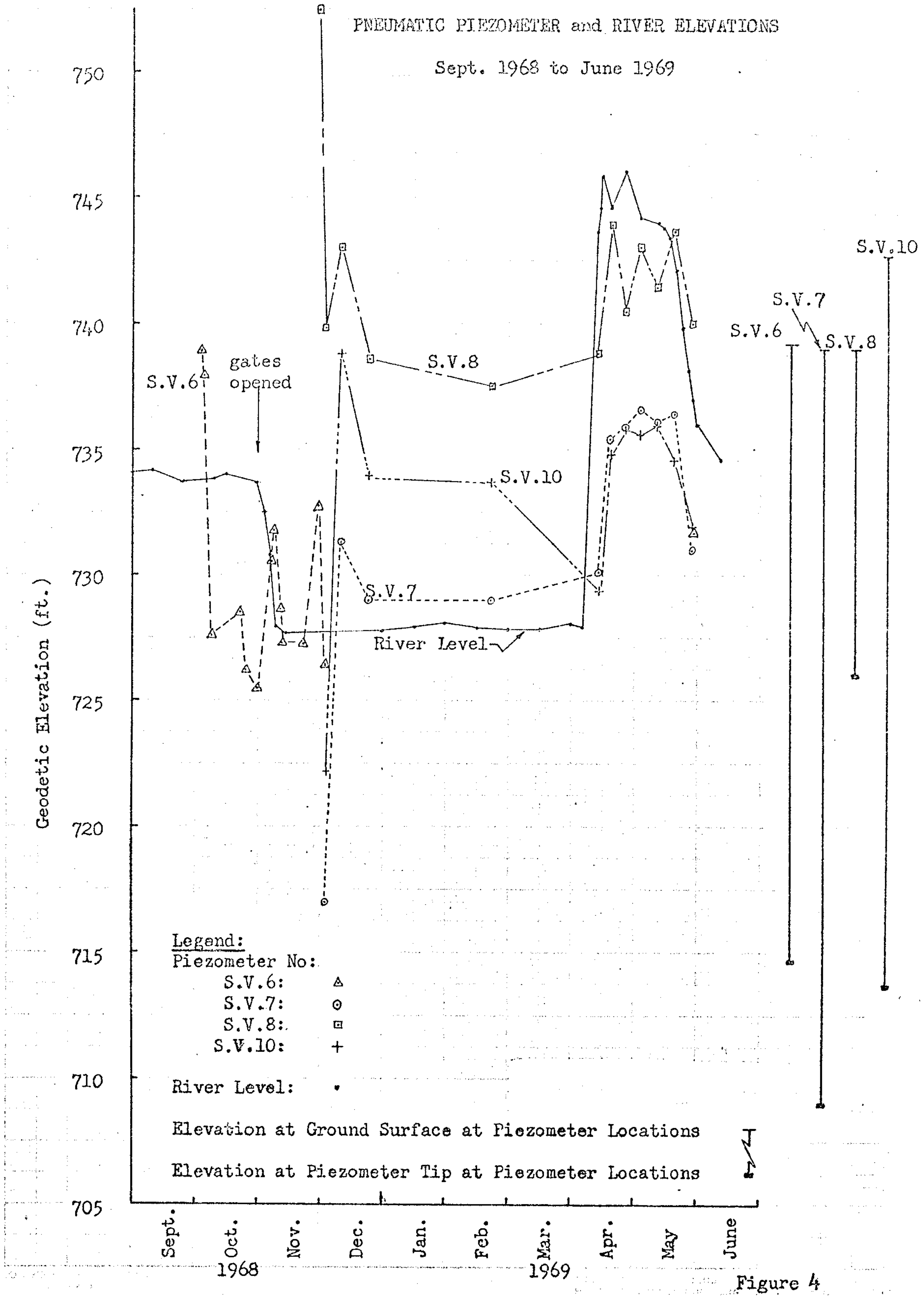
4.3 POREWATER PRESSURE DATA:

The locations of the piezometers installed in the riverbank are shown in Figure 2. The Casagrande piezometers are labelled S.V.1, S.V.2, S.V.3, S.V.4, and S.V.5. The pneumatic piezometers are labelled S.V.6, S.V.7, S.V.8, S.V.10, and S.V.14. Note that the top of the slope is at Sta. 0 + 00 and the edge of the river at normal Summer river level is approximately at Sta. 2 + 00.

Piezometers S.V.3 and S.V.7 are positioned very close to the clay-till interface. Piezometers S.V.2, S.V.6, S.V.10, and S.V.14 are located at elevation 714 feet (geodetic) which is approximately 5 to 6 feet above the clay-till interface. The other four piezometers are located between elevations 724 and 730 and are positioned between Stations 0 + 00 and 1 + 48.

Figure 4 shows the data from the pneumatic piezometers for the period October, 1968 to June, 1969 and of river levels recorded at the James Avenue Pumping Station, located 2.5 miles downstream. This figure also shows the piezometer tip and the ground surface elevations at the piezometer locations.

Piezometer S.V.6 was installed on October 3, 1968 by the manual procedure previously described. The other four pneumatic piezometers were installed on November 29, 1968 utilizing the hydraulic jacking system of a truck-mounted rotary drilling rig. Only one piezometer, S.V.14, failed to operate following installation.



PNEUMATIC PIEZOMETER and RIVER ELEVATIONS

Sept. 1968 to June 1969

Figure 4

Piezometer S.V.6 operated from October 3, 1968 to December 3, 1968. The recorded porewater pressure was 10.5 p.s.i. at approximately 15 minutes after installation, 10.1 psi on October 4th and 5.5 p.s.i. on October 8th. The readings then fluctuated about this latter value until December 3, 1968. Piezometer S.V.6 then failed to operate until May 28, 1969 when a porewater pressure of 7.4 p.s.i. was recorded.

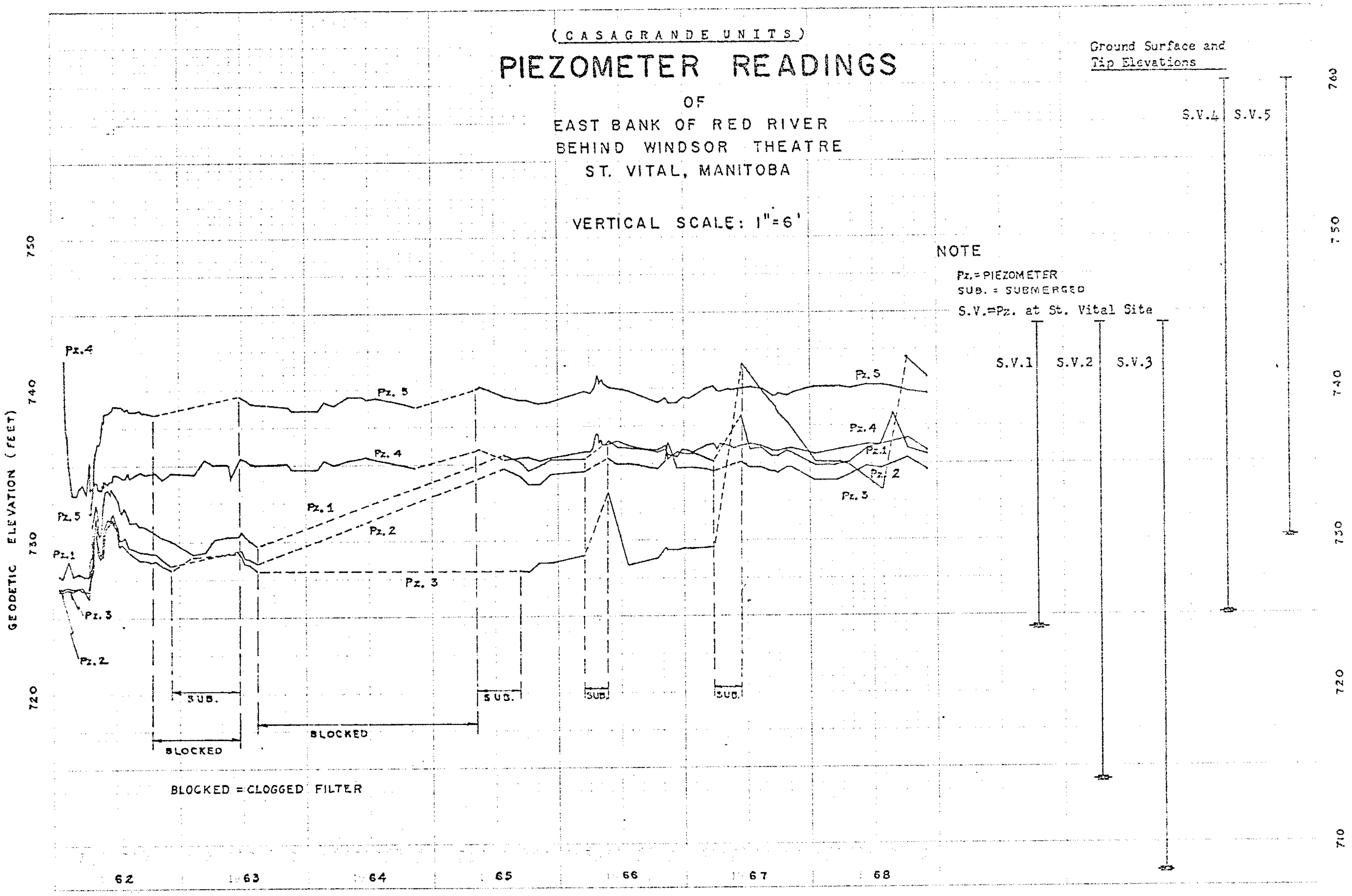
The autumn drawdown of the river took place from November 1 to November 9 of 1968 when the downstream control at Lockport was fully opened, dropping the river level by 5.5 feet.

The porewater pressures, recorded after the drawdown, by piezometers S.V.7, S.V.8, and S.V.10 indicated that the piezometric levels at these locations were higher than the level of the river from the period November 30, 1968 to April 6, 1969. In the spring the river rose 17.9 feet from April 6, to April 15, 1969. During this high water period the elevation changes of the piezometric surface for piezometer S.V.8 (piezometer depth = 11 feet) and piezometer S.V.7 (piezometer depth = 25 feet) lagged river level fluctuations by 5 to 7 days. The maximum recorded porewater pressure at piezometer S.V.7 was 12.0 p.s.i. and was measured on May 3, 1969. On this day the river elevation was 744.2 ft. which was a drop of 1.9 ft. from its maximum of 746.1 ft. recorded on April 26, 1969. At piezometer S.V.8 the porewater pressure during the flood stage attained a magnitude almost equal to the height of the river surface or approximately 5 feet above ground surface. At Piezometer S.V.7 the porewater pressure increase was 7 feet above normal Winter level but was still 3 feet below ground surface. The piezometric surfaces at the 20 to 25 foot depths (S.V.7 and S.V.10) never equalled the elevation of the river level during the flood stage but were only 5 feet less than river levels at the end of May at which time 15 days of drawdown had transpired.

Figure 5 shows the readings recorded from the Casagrande piezometers since early 1962. S.V.3 can presently be regarded as being malfunctional as indicated by the time required for the return of its piezometric level to its natural position following submergence of the plastic standpipe during Spring flooding and periods of high rainfall. Furthermore the submergence of the standpipe at these times has prevented the acquisition of measurements during periods of major interest. The measurements taken at piezometers S.V.4 and S.V.5 indicate that the porewater pressures at these locations remain relatively constant.

As indicated by Figure 4, the data pertaining to piezometers S.V.7, S.V.8, S.V.10, and river levels for the period December 10, 1968 to April 6, 1969, reveals a downward hydraulic gradient in the proximity of Sta. 1 + 50. This implies a flow of water from the river into the underlying glacial till layer. The hydraulic gradient appears to have a downward component, with a minor horizontal component in the direction of the river. This hydraulic feature had been indicated by RENDER[10] when he noted that in central Winnipeg the piezometric surface of the Upper Carbonate aquifer was depressed below the Red River and therefore created a gradient from the river towards the aquifer.

The horizontal hydraulic gradient component towards the river is virtually nullified in the zone ranging from Sta. 1 + 00 to Sta. 1 + 50 during periods of high water levels as indicated by the reduction of porewater pressure at Piezometer S.V.10 to a value equalling the pressure at piezometer S.V.7. This results from the high recharge potential created



(CASAGRANDE UNITS)

PIEZOMETER READINGS

OF

EAST BANK OF RED RIVER

BEHIND WINDSOR THEATRE

ST. VITAL, MANITOBA

VERTICAL SCALE: 1"=6'

NOTE

Pz. = PIEZOMETER

SUB. = SUBMERGED

S.V.=Pz. at St. Vital Site

Ground Surface and Tip Elevations

BLOCKED = CLOGGED FILTER

Figure 5

by the high river level, which significantly increases the piezometric level in the section of the riverbank adjacent to the river.

Piezometers S.V.4 and S.V.5, which are located at Sta. 0 + 00, also indicate a slight downward hydraulic gradient for this portion of the riverbank. Apparently the river edge is too far from these piezometers to significantly affect their piezometric levels. The fluctuations in the river levels are not reflected in the porewater pressures recorded at piezometers S.V.4 and S.V.5.

4.4 SLIP SURFACE OBSERVATIONS

The position of several points of the slip surface were determined from data determined by the two slope indicators, a sub-soils profile, and a ground surface profile. The two slope indicators were installed on January 13th, 1969, at Stations 0 + 84 and 1 + 34 as indicated by Figure 2. Figure 6 shows the slope movement at each slope indicator as recorded on December 17, 1969.

The most significant feature revealed by this data was that the failure zone existed immediately above the clay-till interface, at least between Sta. 0 + 84 to Sta. 1 + 34. This segment of the failed section is moving in a lateral motion towards the river and moved at a rate of 3.25 inches per annum in the year 1969.

The ground surface-slip surface intersection was readily indicated by the scarp at Sta. 0 + 09 (Figure 1). Ground surface cracks, further down the slope, which were in a direction parallel to the river also indicated some internal movements and disturbances within the failed section. Since the location of the failed surface was not visible at the toe, the resulting assumption postulated that the failure surface terminated beneath the water level.

TOTAL SLOPE MOVEMENT

ST. VITAL, MANITOBA

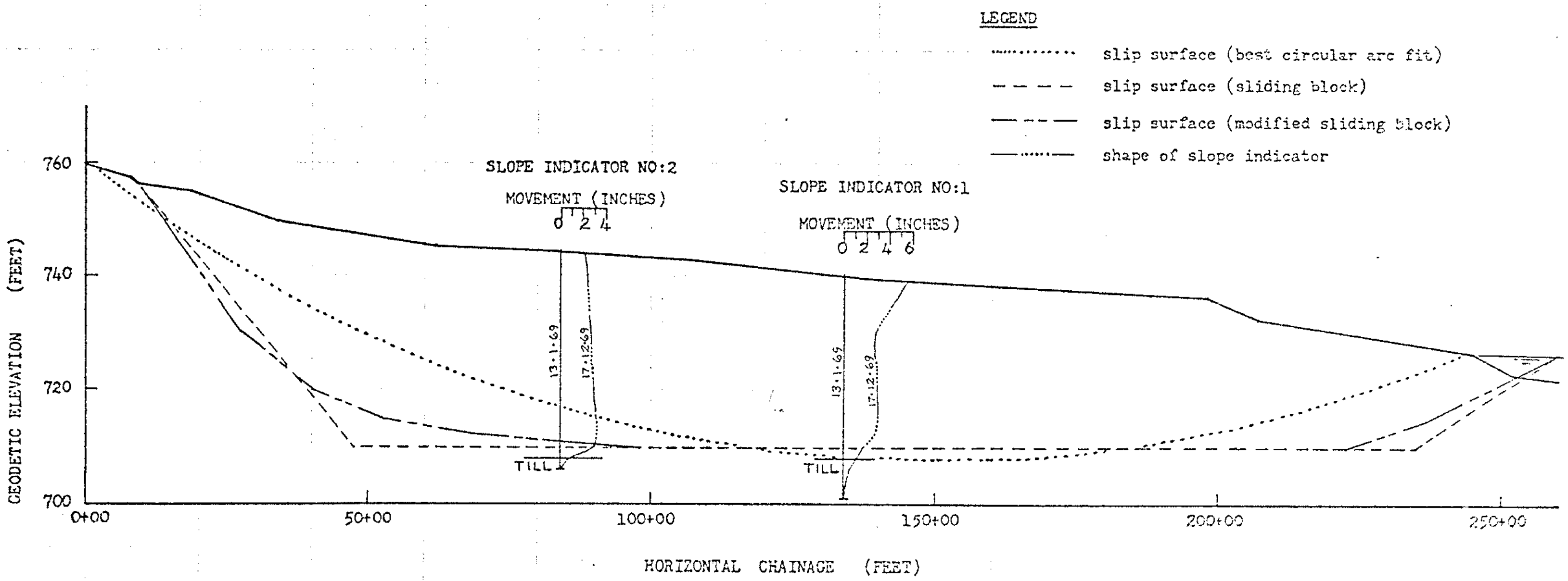


Figure 6

CHAPTER 5

THEORETICAL CONSIDERATIONS

5.1 SLOPE STABILITY THEORY:

The slope stability analysis used was the limit equilibrium analysis. This form of analysis compares the shear strength mobilized along the slip surface to the shear strength available on this same surface. Three methods incorporating the limit equilibrium analysis are (1) Wedge Method, (2) Friction Circle Method, and (3) Method of Slices.

The Wedge Method can be used when the failure surface can be described by several straight lines. A detailed description of this method is given by SHERARD et al[11], Corps of Engineers[12], and SULTAN and SEED[13]. The Friction Circle Method considers only the whole free body and makes assumptions regarding the distribution of normal stresses along the failure surface. A general description of this method is given by TAYLOR[14].

The "Method of Slices", which is the most widely used method, divides the free body into a number of vertical slices, and the equilibrium of each slice is considered. This method was developed by FELLENIUS[1] in Sweden in about 1927. Further developments of this method are presented by BISHOP[2], MORGENSTERN and PRICE[15], SPENCER[16], JANBU[3], and BELL[17].

5.2 CIRCULAR ARC SLIP SURFACE METHOD OF SLICES:

Essentially the "Method of Slices" consists of analyzing a section of a riverbank or embankment and considering the equilibrium of the entire section. A statically indeterminate problem prevails, and a set of assumptions are required to reduce the number of unknown variables to make the problem statically determinate. This approach implies firstly that a range of possible solutions exist and secondly that knowledge, experience and intuition are required to determine which solution is most realistic.

The "circular arc slip surface method of slices" assumes that the slip or failure surface is circular, or that the failure surface can be approximated as being circular. This assumption greatly simplifies the general solution, in that the equilibrium of the sum of the moments for the entire mass can easily be computed about the center of the circular arc. The moment of the driving force is equated to the moment of the resisting force. The driving force is the total weight, W, of the embankment as illustrated in Figure 7, whereas the resisting force is the mobilized shearing strength of the soil, S_m.

Figure 7(a) illustrates the forces acting on a single slice that would exist in the dashed portion of the embankment section of Figure 7. The forces acting on such a slice are as follows:

1. The total weight of the slice, W.
2. The total reaction, P, normal to the base; the two components of this force are:
    - (i) the force, P', due to the effective or intergranular stress, and
    - (ii) the force, U, due to the porewater pressure, and is equivalent to uL.

      Where:

      u = unit porewater pressure, and

      L = length of base of slice.

      b = slice width.

Therefore $P = P' + U$ or $P = (p' + u)L$

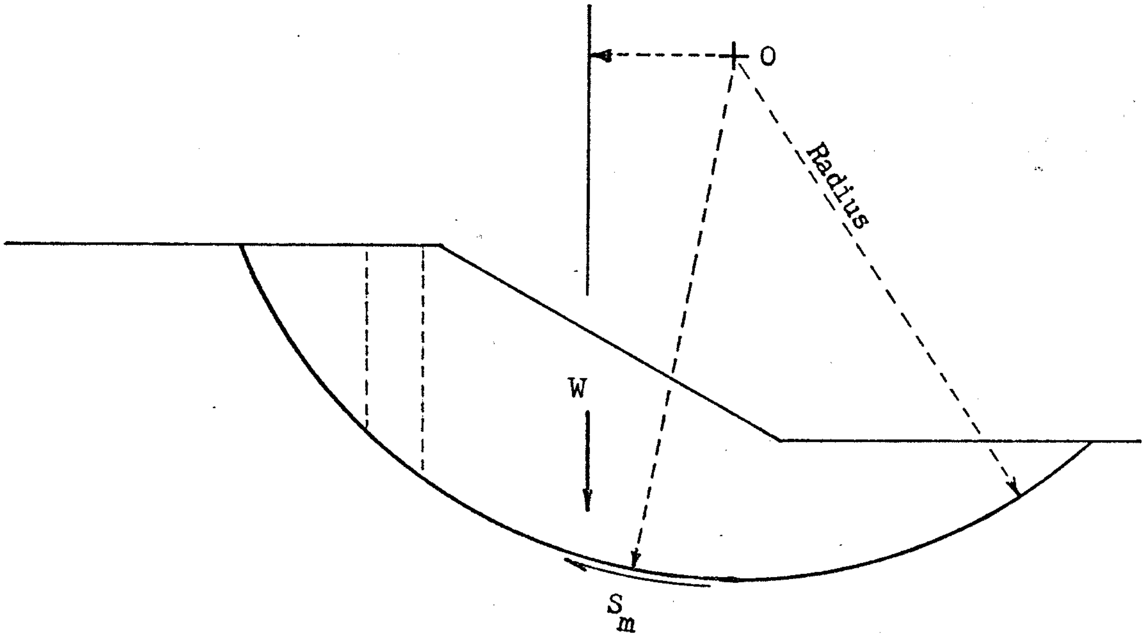


Figure 7: FORCE MOMENTS ABOUT CIRCULAR ARC CENTER

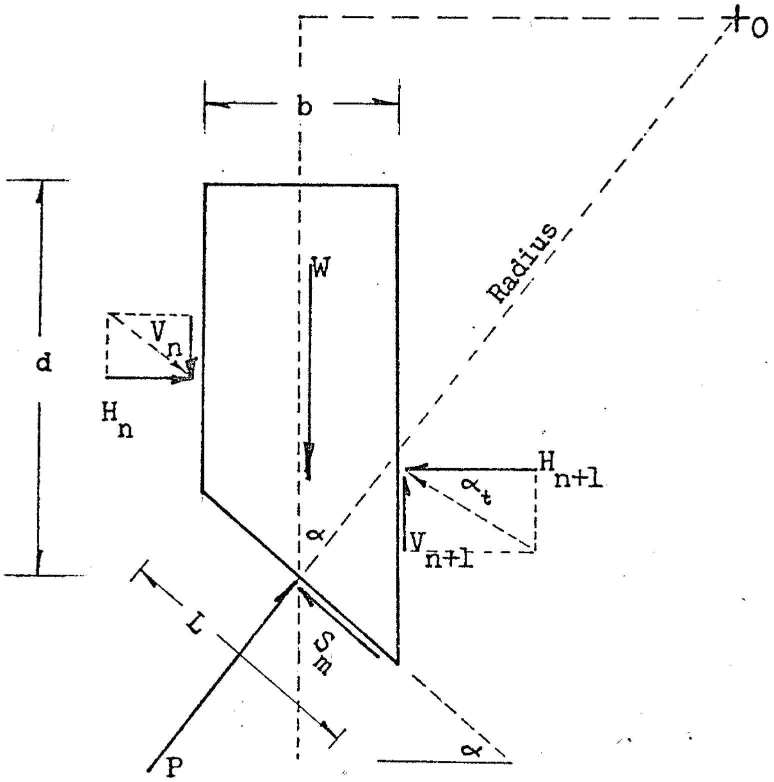


Figure 7(a): FORCES ACTING ON A SLICE

3. The mobilized shear force as defined by Coulomb's shear strength equation:

$$S_m = \frac{c'L}{F} + P' \frac{\tan \phi'}{F}$$

Where:

c' = cohesion in terms of effective stress.

ϕ' = angle of shearing resistance in terms of effective stress.

F = the Factor of Safety for the stability of the slope.

The definition of the Factor of Safety is as follows:

$$F = \frac{\text{available shear strength}}{\text{shear strength required for equilibrium}}$$

4. The horizontal interslice forces H_n and H_{n+1}.
5. The vertical interslice forces V_n and V_{n+1}.

In the circular arc slip surface method, the safety factor is obtained by summing the moments about the center of the failure arc. The difficulty begins with the attempt to evaluate the distribution of the effective normal reaction to the base, P', along the slip surface.

P' is determined in the "Fellenius Method of Slices" by summing the forces of a slice in a direction perpendicular to the slip surface. The derived equation for the Factor of Safety is:

$$F = \frac{1}{\sum W \sin \alpha} \sum \left[c'b \sec\alpha + (W \cos\alpha - ub \sec\alpha) \tan \phi' \right]$$

By summing the forces perpendicular to the slip surface the implied assumption is that the inter-slice forces acting on the sides of any slice have zero resultant in the direction normal to the failure arc for that slice. Error results in the calculation of the Factor of Safety as the angle between the base of each slice and the horizontal, α, is not constant. Further error results if the angle of shearing resistance, ϕ', varies. The error increases with the increasing central angle of the failure arc, because the value of P' is underestimated along the steeply inclined portion of the failure surface. P' may become negative at this steeply inclined portion if a large porewater pressure force, U, exists. Errors as high as 60% (Ref. 18) can result for problems with deep failure surfaces and high porewater pressures.

In the "Bishop's Method of Slices" (Ref. 2), P' is determined by summing the vertical forces of a slice. The derived equation for the Factor of Safety is:

$$F = \frac{1}{\Sigma W \sin\alpha} \sum \left[\left\{ c'b + \tan\phi' \quad \left[(W-ub) + (V_n - V_{n+1}) \right] \right\} \frac{\sec\alpha}{1 + \frac{\tan\phi'}{F} \tan\alpha} \right]$$

This equation implies that an initial assumption of the distribution of vertical forces is required. Furthermore, this distribution of vertical forces is to be adjusted until equilibrium conditions are fully satisfied for each slice.

This type of solution requires lengthy computations and adjustments to obtain the final safety factor. This equation was then modified to yield the "Simplified Bishop's Method of Slices" by assuming that the inter-slice forces acting on the sides of a slice have zero resultant in the vertical direction for that slice. The equation for the factor of safety reduces to:

$$F = \frac{1}{\sum W \sin \alpha} \sum \left[\left(c'b + \tan \phi' \; (W-ub) \right) \frac{\sec \alpha}{1 + \frac{\tan \phi' \; \tan \alpha}{F}} \right]$$

But since the resultant of the inter-slice forces does not act in a horizontal direction for all slices, the calculated Factor of Safety is in error. Studies by BISHOP[2], WITHMAN and MOORE[19], and WITHMAN and BAILEY[18] have shown that this error is 7% or less and usually only 2% or less.

5.3 NON-CIRCULAR SLIP SURFACE METHOD OF SLICES

The "Janbu Method of Slices for a Composite Surface" (Ref. 3) was employed to calculate the Factor of Safety for the cases where the slip surface could not be approximated by a circular arc.

In the derivation of the equation for this method the moment of equilibrium of each slice is taken about a point, C, as shown in Figure 8. The point, C, is at the intersection of the four vectors, W, $\vec{H}_n + \vec{V}_n$, $\vec{H}_{n+1} + \vec{V}_{n+1}$, and $\vec{P} + \vec{S}_m$. A resulting moment equation about point C is:

$$\left[V_{n+1} - H_{n+1} \tan \alpha_t \right] \frac{b}{2} = 0 \qquad (1)$$

This equation implies that the positions and direction of the resultant of the inter-slice forces acting on the slice must be known in order to produce a statically determinate solution. As these are not positively known in advance, they must be chosen by trial and error such that the final solution results in static equilibria. Summing the forces in the vertical direction yields:

$$\left[W - (V_{n+1} - V_n) \right] - (u + p') \, L \cos \alpha - S_m \, L \sin \alpha = 0 \qquad (2)$$

Summing the forces in the horizontal direction yields:

$$H_n - H_{n+1} + (u + p') \, L \sin \alpha - S_m \, L \cos \alpha = 0 \qquad (3)$$

The Mohr-Coulomb equation defining shear strength is:

$$S_m = \frac{c'}{F} + P' \frac{\tan \phi'}{F} \tag{4}$$

The complete derivation of the solution incorporating the four basic equations above is as follows:

Substitute (4) into (3) and divide by b:

$$P' = \frac{\left[\dfrac{W - (V_{n+1} - V_n) - u}{b}\right] - \dfrac{c'}{F}\tan\alpha}{1 + \dfrac{\tan\alpha \tan\phi'}{F}} \tag{5}$$

Substitute (5) into (4) and multiply by L:

$$S_m L = \left\{\frac{c'b}{F} + \left[W - (V_{n+1} - V_n) - U\right]\frac{\tan\phi'}{F}\right\} \frac{1}{\cos\alpha\left(1 + \dfrac{\tan\alpha \tan\phi'}{F}\right)} \tag{6}$$

Multiply (2) by $\tan\alpha$ and equate to (1):

$$\left[H_{n+1} - H_n\right] = \left[W - (V_{n+1} - V_n)\right]\tan\alpha - \frac{S_m L}{\cos\alpha} = B - \frac{A}{F} \tag{7}$$

Where: $B = \left[W - (V_{n+1} - V_n)\right]\tan\alpha$

$$A = \left\{c'b + \left[W - (V_{n+1} - V_n) - U\right]\tan\phi'\right\} \cdot \frac{1}{\cos\alpha\left(1 + \dfrac{\tan\alpha\tan\phi'}{F}\right)}$$

The summation of the horizontal inter-slice forces must equal zero for the condition of horizontal equilibrium to exist. Therefore $\sum(H_{n+1} - H_n) = 0$ and equation (7) becomes:

$$F = \frac{\sum\left\{c'b + \left[W - (V_{n+1} - V_n) - U\right]\tan\phi'\right\}\dfrac{1}{N_\alpha}}{\sum\left[W - (V_{n+1} - V_n)\right]\tan\alpha} = \frac{\sum A}{\sum B} \tag{8}$$

Where: $N_\alpha = \cos^2\alpha\left(1 + \dfrac{\tan\alpha\tan\phi'}{F}\right)$

Equation (8) is the Factor of Safety by the Janbu Method and is not readily determined as three unknowns exist; namely F, V_n, and V_{n+1}.

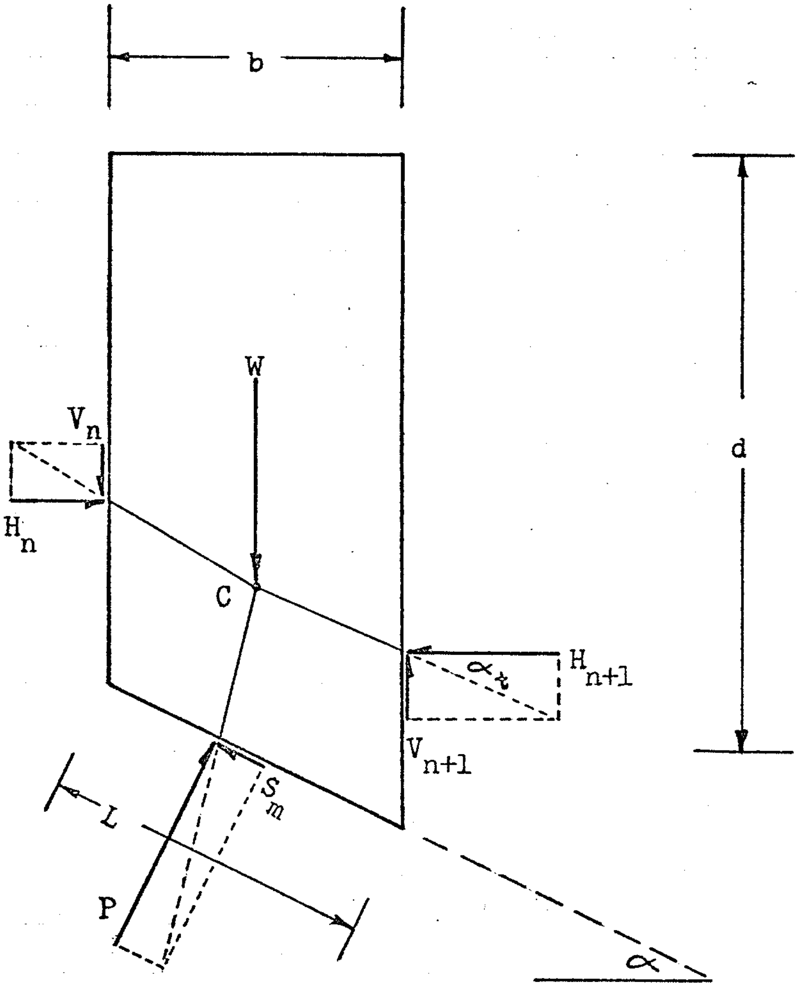


Figure 8 : FORCES ACTING ON A SLICE

An initial Factor of Safety, Fo, is determined by assuming that the resultant of the vertical inter-slice forces equal zero. Equation (8) becomes:

$$F_o = \frac{\sum \left[c'b + (W - ub) \tan \phi' \right] \frac{1}{N_\alpha}}{\sum W \tan \alpha} = \frac{\sum A_o}{\sum B_o} \tag{9}$$

A reiteration process is required for solution due to the presence of F on both sides of the equation. This initial solution is similar to the "Simplified Bishop's Method" as it implies that the resultant interslice forces act in a horizontal direction.

To strive for a rigorous solution implies that some committment must be made at this point to define a function describing the positions of the inter-slice forces. This is accomplished by positioning a line, known as the "line of thrust", throughout the analysed section which defines the location of inter-slice forces. The line of thrust is generally assumed to exist either through or somewhat above the lower-third point of each slice in consideration for the physical capacity of the soil to withstand tensile forces. Since this line defines the direction of action of the inter-slice force vector at any horizontal co-ordinate in the section, the calculation of $\tan \alpha_t$, (as per figure 8), can be performed for each slice.

Since boundary conditions imply that no external forces act on the mass, then:

$V_1 = 0$ and $H_1 = 0$ at $n = 0$ and therefore:

$$V_{n+1} = \sum_0^n dV = \sum_0^n (V_{n+1} - V_n) \tag{10}$$

$$H_{n+1} = \sum_0^n dH = \sum_0^n (H_{n+1} - H_n) \tag{11}$$

Substitute (11) and (7) into (1):

$$V_{n+1} = \tan \alpha_t \sum_{o}^{n} (B - \frac{A}{F}) \tag{12}$$

Employing equation (12), values of V_{n+1} are calculated for all vertical sections between each slice, and a modified Factor of Safety is determined from equation (8). This procedure is repeated until the required degree of accuracy is obtained.

Furthermore, as the calculation process yields values for the vertical and horizontal inter-slice forces, their magnitude and direction of action should not imply a physical imbalance. If the imbalance exists, then a modification of the line of thrust is mandatory as well as another set of computations to determine a revised value for the Factor of Safety.

5.4 SHEAR STRENGTH PARAMETERS:

Since insitu porewater pressures were employed in the stability analysis of the riverbank, only soil shear strength parameters in terms of effective stress were considered. A typical clay in the Winnipeg area develops a stress-strain curve as shown in figure 9, (Ref. 22). This type of curve also exhibits the shear strength of a clay at a relatively large strain and can best be produced by drained direct shear tests. Figures 9 and 10 illustrate the "peak" shear strength parameters which occur at maximum shear stress, and the "residual" shear strength parameters which exist along the sheared plane of the clay.

Skempton[20] has observed for overconsolidated clays that in the transition from peak to residual, the cohesion intercept disappears completely and the angle of shearing resistance decreases from 1 to 10 degrees. Direct shear tests conducted on a clay from a site at the University of Manitoba by MUIR[21], indicated average "peak" values to be

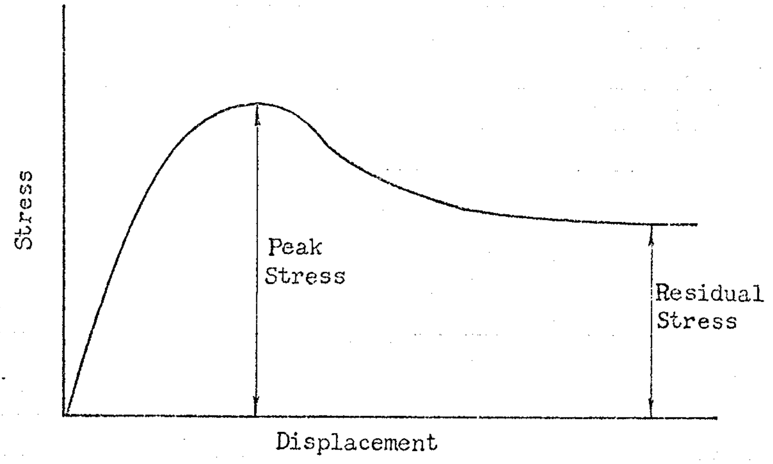


Figure 9: STRESS-STRAIN CURVE

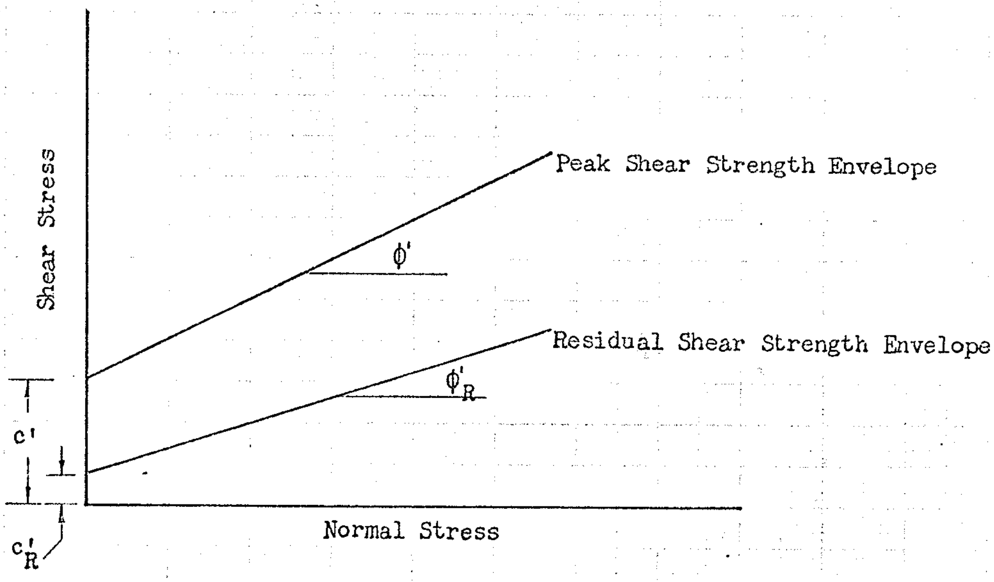


Figure 10: MOHR-COULOMB SHEAR STRENGTH ENVELOPES

$\phi' = 14^\circ$, $c' = 3$ p.s.i., and the average "residual" values to be $\phi'_R = 13^\circ$, $c'_R = 0$. Tests conducted on Manitoba clays by SUTHERLAND[8] at Glasgow indicated a much greater reduction in the transition from "peak" to "residual" shear strength (see Table 2).

Mechanisms possibly responsible for this strength reduction as proposed by SKEMPTON[20] include:

1. The macroscopic fissures, joints and slickensides, present in many clays, act as discontinuous planes of weakness with inherent strength parameters approaching residual values.

2. Furthermore these weak planes act as stress concentrators because additional stress is imposed on the clay at some other point.

3. It is possible that shear creep, which is the application of stresses applied over periods of years, does not produce as high a strength as measured by laboratory tests where the stresses are applied in several weeks.

4. Reduction in strength of a clay at shallow depths can result from seasonal variations of water content and temperature.

Regardless of the initiating mechanism, the strength along the developing slip surface eventually approaches residual values. Therefore it appears to be logical to use "residual" strength parameters in analysing the long term slope stability of riverbanks that have previously failed but now appear to be stabilized.

5.5 COMPUTER PROGRAM

As a part of this thesis, a slope stability computer program was developed to achieve the following objectives:

1. To conduct circular arc slip surface analyses by the Fellenius and Simplified Bishop's Methods.

2. To analyse non-circular slip surfaces by the Janbu Method.
3. To obtain the results of (1) and (2) quickly and with a high degree of accuracy.

To accomodate the computer program, the profile of the slope is described by a series of straight lines. Straight lines are also employed to describe soil layers, water surface, piezometric surface, other structures or loading conditions pertinent to the analysis. In the case of the non-circular slip surface analysis, straight lines also describe the thrust line and slip surface. A "material type" number is assigned to each straight line to enable the computer to recognize the function of each line during the analytical process. Logical arrangement of input data facilitates the physical simulation of the majority of conditions that can be encountered in the field. The flexibility of the program is illustrated by the following summary of available options:

1. Analysis type:
    - (a) Simplified Bishop's Method
    - (b) Fellenius (Simplified, or Swedish Circle) Method, or,
    - (c) Janbu Method.
2. Shear Strength Parameters:
    - (a) Total Stress, or,
    - (b) Effective stress.
3. Pore Water Pressure Description:
    - (a) Piezometric Surface, and/or,
    - (b) Pore water pressure parameter for each soil type.

The program takes into account the effect of vertical external loadings. Lateral forces induced by earthquake or other vibrational actions are excluded.

The program documentation, which is essentially a "User's Manual" is presented in Appendix "A".

CHAPTER 6

SLOPE STABILITY ANALYSIS

6.1 GENERAL

It may be postulated that the original riverbank existed with a stable natural slope steeper than at present. The original strength of the clay in the riverbank would have been at the "peak" state as found for the undisturbed clay samples. The decrease in strength with time, however, led to the development of a slip surface or slip zone that induced slope movement as a result of local stress concentrations and overstressing.

The overstressing condition was probably developed by a combination of the following factors:

1. The progressive action by river currents and/or massive ice movements causing erosion at the toe and thereby resulting in an equivalent steeper slope.
2. The occurrence of a piezometric condition that induced sufficient strength decrease to generate a failure.

The first contributing factor as cited above is self-explanatory and is evident at various locations along the Red River. But the second factor is more complex and requires piezometric data for several years to determine the most severe porewater pressure condition. Heavy precipitation, severe and rapid drawdown following high river levels could create a piezometric regime within the riverbank to sufficiently reduce the strength of the insitu soil to initiate a failure.

It is possible that the porewater pressure developed within the local riverbanks are not attaining magnitudes as high as have been experienced in the past. Three factors which account for this are:

1. Downstream Control Structure at Lockport,
2. Red River Floodway and Portage Diversion, and
3. Ground Water Wells.

The planned control of the river level by the downstream control structure at Lockport, creates two features which have a direct relationship on the stability of upstream riverbanks within Central Winnipeg. The first feature occurs generally in May, following peak flow levels, when the gates of the control structure are positioned to maintain the river level at the specified summer level of approximately six feet above winter river level. The employment of the gates at this time minimizes a potential danger due to the retardation of the natural drawdown. The second significant feature occurs in the beginning of November when the gates are suddenly opened, and the river is allowed to drawdown, without restraint, approximately six to seven feet. As indicated by Figure 4, drawdown was relatively rapid (a period of nine days) and it lowered the level of the river below the piezometric level of the clay-till interface within the riverbank.

The second factor, which has been fully effective only since early 1970, consists of the partial diversion of the two rivers traversing the city of Winnipeg in an attempt to control, within reasonable limits, the river levels at time of potential Spring Flooding. This anticipated temperance implies a reduced maximum river height during peak flow periods and therefore minimizes the potential of experiencing a critical instantaneous drawdown.

The most significant of the three factors previously referred to is that of the local ground water wells. RENDER[10], illustrates graphically the estimated groundwater pumping rates within Metropolitan Winnipeg since 1890. In summary, the pumping rate rose steadily to a peak of 10 million gallons per day in 1919, and then abruptly dropped to approximately 1 million gallons per day in that same year. Since then pumpage has increased to the present rate of 8 million gallons per day. The significance of the pumping rate is that it has a direct effect on the level of the piezometric surface of the Upper Carbonate aquifer, which is the main aquifer, for the local ground water wells. The existence of fissures in the dolomitic bed rock and the cemented glacial-till could provide a contact between the clay layer of the riverbank and the Upper Carbonate Aquifer. This contact could cause the piezometric level in the aquifer to be reflected in the piezometric level of the clay-till interface. In central Winnipeg, which is the area of maximum pumpage, the piezometric surface of the Upper Carbonate aquifer has been depressed extensively. In the general area of the St. Vital riverbank this piezometric surface had fluctuated in the range of 700 to 725 feet (Geodetic Elevations) during the years 1964 to 1968 inclusive. The minimum level occurs in the summer as the major portion of ground water is employed for the purpose of air conditioning. Therefore this artifically produced depression of the Upper Carbonate layer piezometric surface indirectly enhances the stability of the riverbank as this depressed surface is responsible for the existence of the predominantly downward hydraulic gradient that was observed within the St. Vital riverbank. Conversely, if the pumpage was of insufficient magnitude to significantly depress the piezometric surface of the underlying aquifer the predominate component of the hydraulic gradient within the riverbank would be other than downward. This implied geohydrology condition would generate riverbank instabilities at a greater rate than exists at present.

6.2 CIRCULAR SLIP SURFACE ANALYSIS

The slope stability analysis, conducted for the riverbank, assumed its most probable critical condition to correspond with the river level at its low "Winter" level and the piezometric surface to correspond to that determined for the clay-till interface. Near the toe the piezometric surface was near ground surface and then leveled off to elevation 735 further back into the riverbank.

The Simplified Bishop's Method and the Fellenius Method as previously discussed in Chapter 5, were used for the analyses. All computations were handled by the Computer Program described in Chapter 5. Since the slope indicators revealed that the slip surface existed at the clay-till interface each analysis was conducted with the circular arc tangent to this interface.

The resulting "factor of safety" contours are shown in Figure 11 (Simplified Bishop's Method) and Figure 12 (Fellenius Method). Both methods indicated that the implied critical circle was near the toe of the slope that had a localized approximate slope of 3.5 to 1. The minimum calculated factors of safety were 0.74 by Simplified Bishop's Method and 0.45 by the Fellenius Method. But the slope indicator data indicated that the position of the actual slip surface did not correspond to the theoretically implied positions. The factors of safety for the slip surface passing through the two control points as indicated by the "slope indicators" (referred to as slip surface No. 1, Figures 11 and 12) were

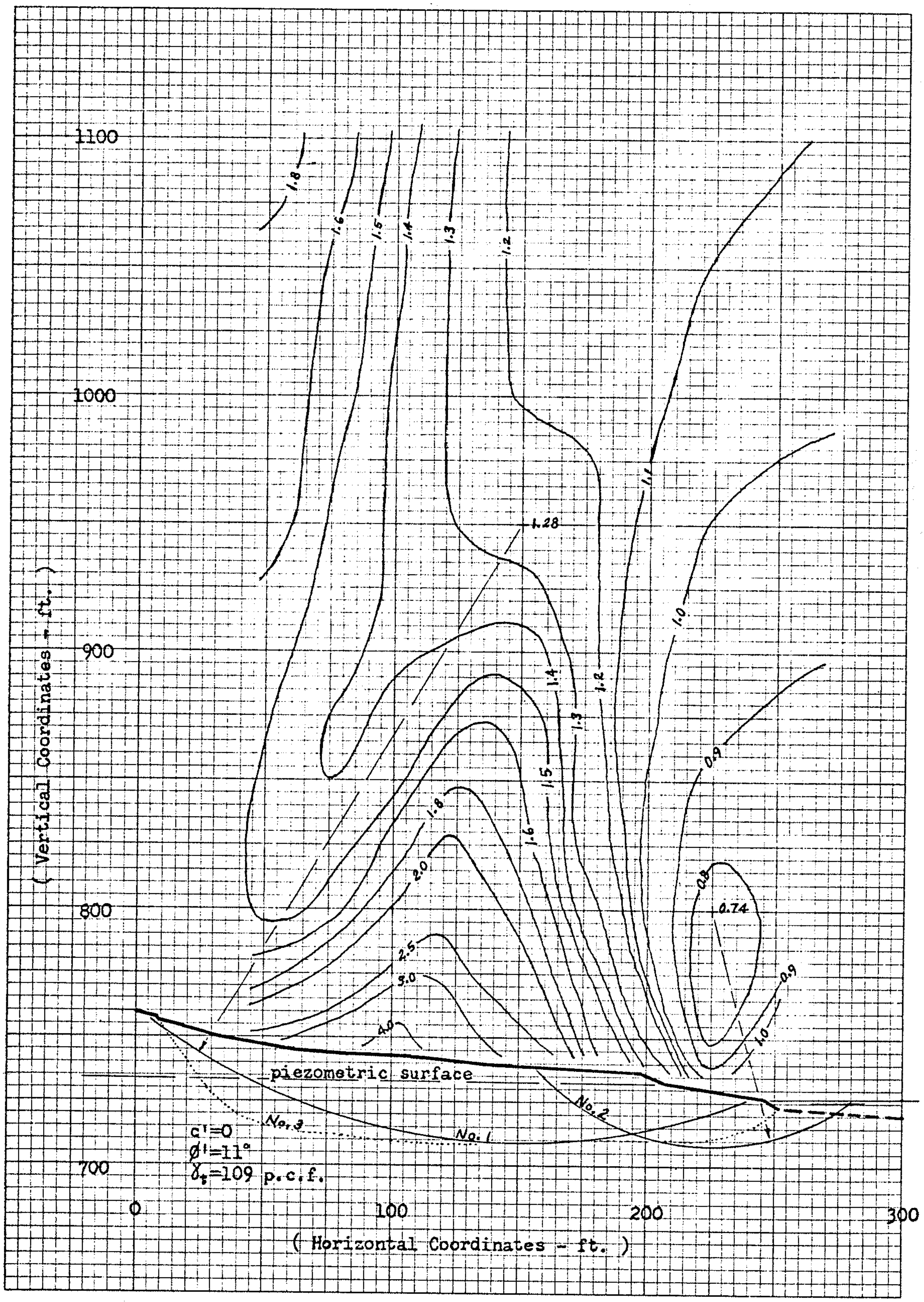


Figure 11: FACTORS OF SAFETY BY "SIMPLIFIED BISHOP'S" METHOD

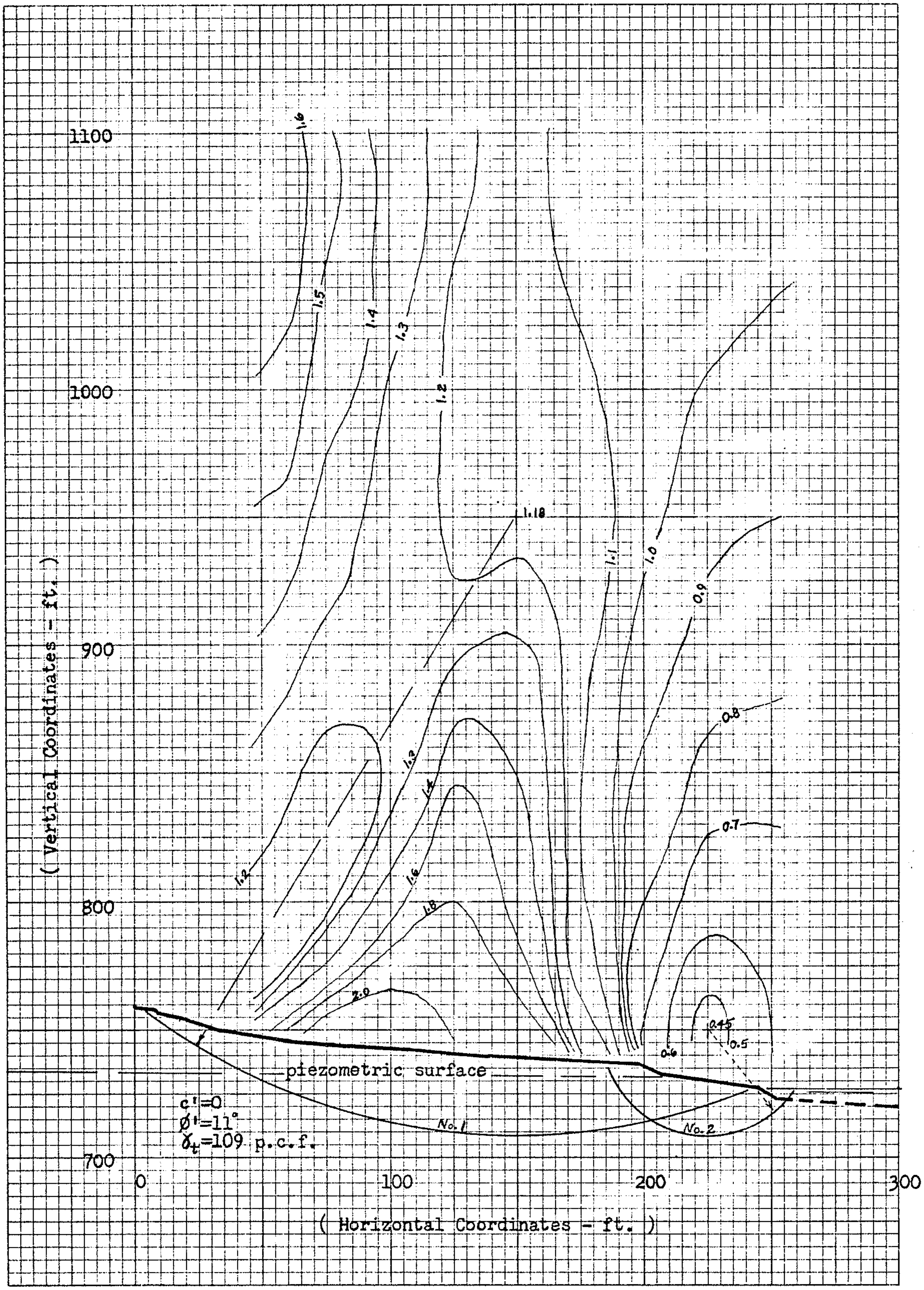


Figure 12: FACTORS OF SAFETY BY "FELLENIUS" METHOD

appreciably higher than those calculated for the implied critical slip surface (slip surface No. 2).

But it should be noted that the shear strength parameters used were typical effective "residual" values ($c' = 0.0$ psi, $\phi' = 11^{\circ}$) for Winnipeg clays. These parameters were only partly valid for slip surface No. 2 as the major segment of the circular arc actually passes through a relatively undisturbed soil zone which implies shear strength parameters approaching "peak" strength values.

But effective "residual" shear strength values can be applied to slip surface No. 1, which is the best circular arc approximation of the assumed slip surface. A factor of safety of 1.3 was given by the Simplified Bishop's Method and 1.2 by the Fellenius Method. The factors of safety by these two methods were in excess of unity, even though the riverbank was in a state of movement.

The unsatisfactory aspect of these analyses is that the shape approximation of the slip surface by the circular arc is not compatible with a relatively long gentle slope and relatively shallow position of the failure or slip zone. An improved shape approximation, as indicated by slip surface No. 3 of Figure 11, complies with the control points of the "slope indicators", conforms to the fracture evident at the main scarp, and the geometry at the toe of the bank.

6.3 NON-CIRCULAR SLIP SURFACE ANALYSIS

The non-circular slip surface analysis was conducted to evaluate the stability of the riverbank by employing the failure surface shape approximation as indicated by field observations as by slip surface No. 3 of Figure 11. The modified approximation as shown in Figure 13 is actually that of the Sliding Block Analysis where the sliding mass is divided into three parts, an upper active wedge, a neutral block, and a passive wedge. The approximate location and shape of the slip surface was determined as follows:

1. Neutral Block: Slides on a horizontal plane at the approximate depth as indicated by the "slope indicators". This plane exists in the clay layer immediately above the glacial till layer.
2. Upper Active Wedge: Commences at the slip surface-ground surface intersection at the main scarp, then proceeds downwards at an angle of $45^{\circ} + \phi'/2$ from the horizontal.
3. Passive Wedge: Commences at the toe of the riverbank, then proceeds downwards at angle of $45^{\circ} - \phi'/2$ from the horizontal.

Applying the same piezometric surface as in the previous circular arc analysis, and assigning residual shear strength parameters to the soil in zone of the slip surface, the sliding block was then analyzed by the Janbu Method of Slices. The equations employed are as in Chapter 5 and computations were facilitated by the computer program. An initial assumption was that the resultant of the interslice forces would act predominantly in a horizontal direction and therefore the thrust line was defined to act horizontally. Figure 13 illustrates the results of the analysis which gave a factor of safety of 1.12. The plot illustrates the magnitude of the horizontal interslice forces along the entire length of the section and reveals a peak at the transition plane of the Active and Neutral Blocks. It is apparently obvious that the abrupt change in

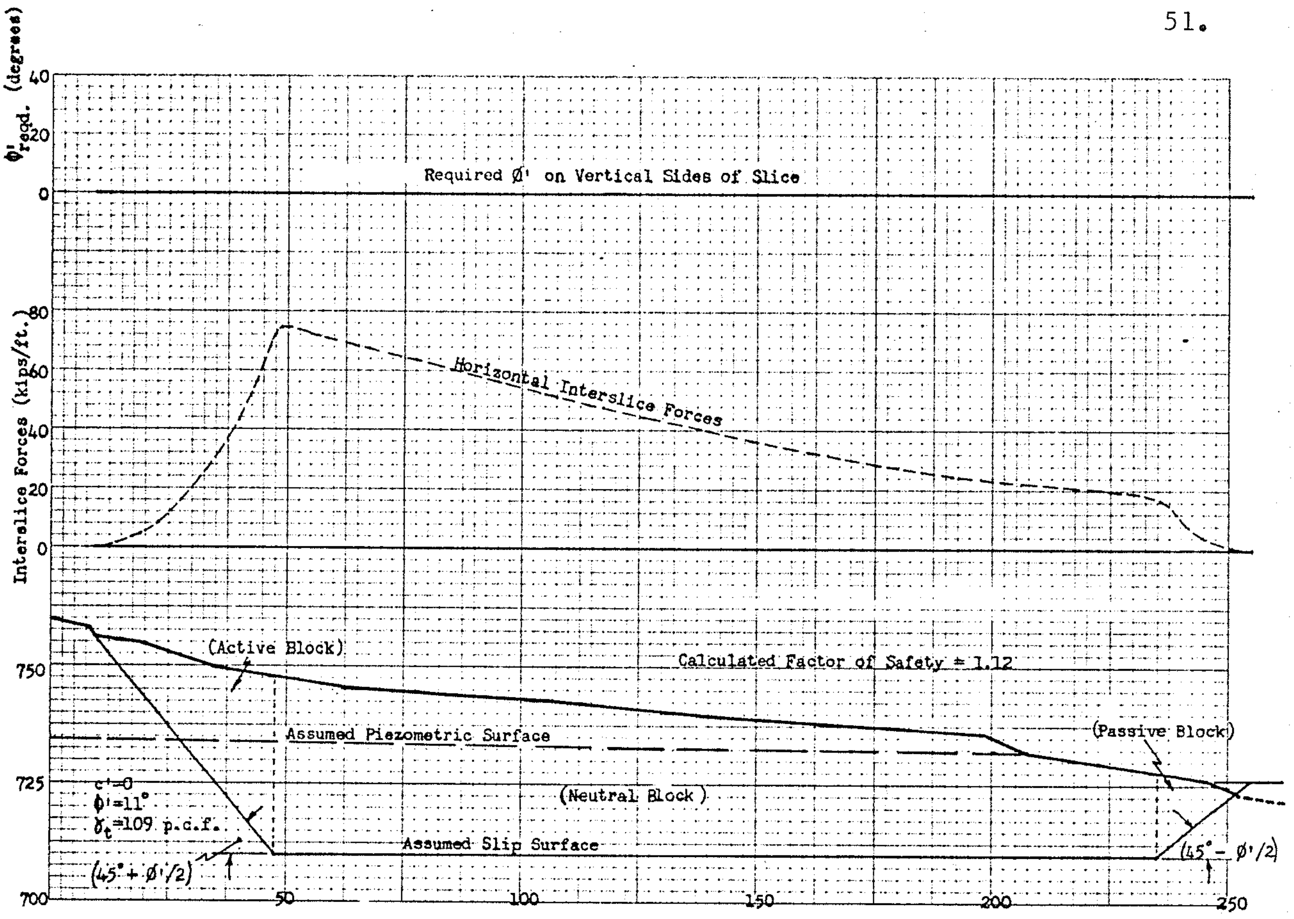


Figure 13: Initial Sliding Block Analysis

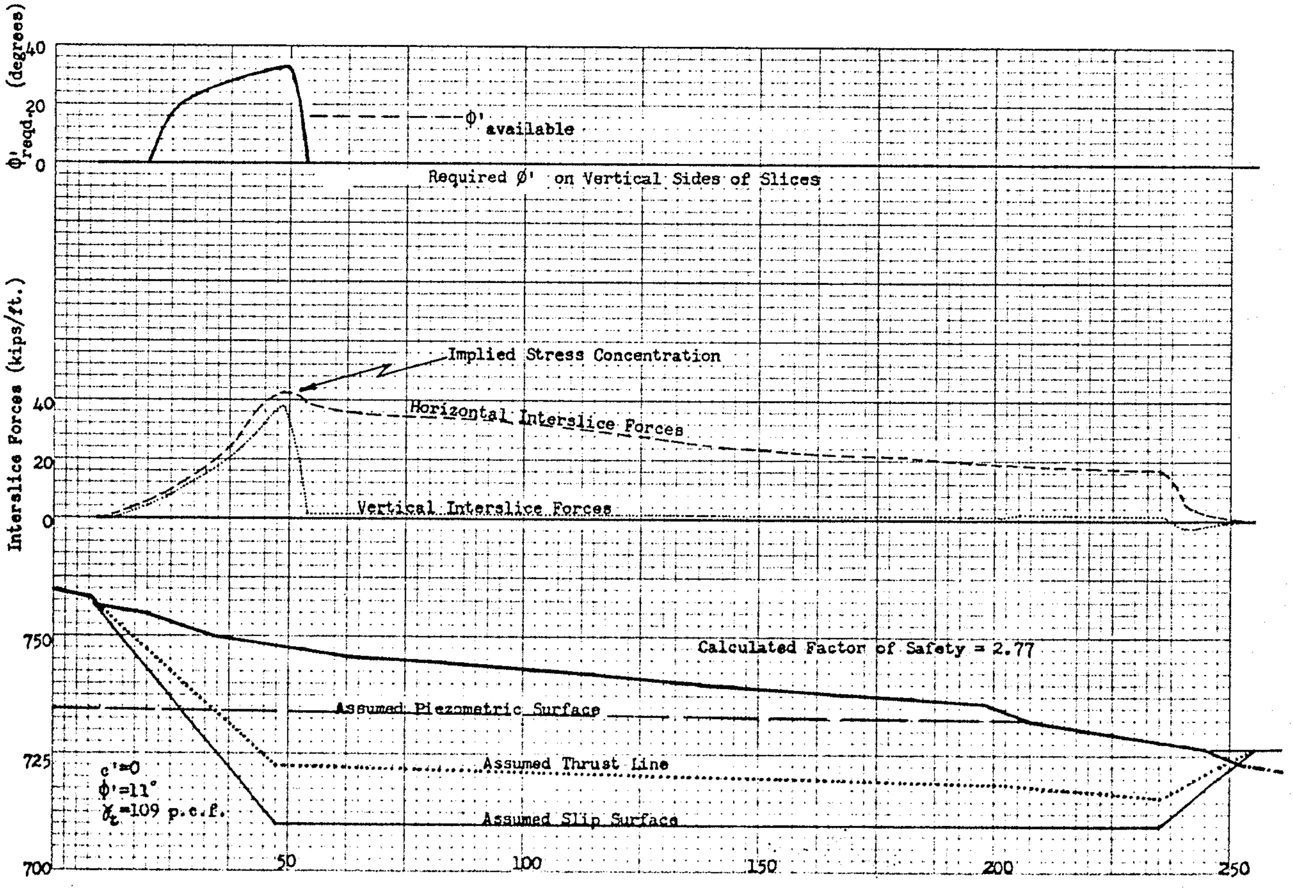


Figure 14: Sliding Block Analysis With Modified Thrust Line

direction of the slip surface has accounted for the implied stress concentration.

To evaluate whether this implied stress concentration could be sustained by the soils within the riverbank the equation tan $\emptyset'$ req'd = $(V_{n+1} - c'd)/H_{n+1}$ was employed (Ref. 18). This equation analyses the vertical forces along the vertical sides of slices to determine whether the required shear strength to provide equilibrium does not exceed the available shear strength. The comparison of the required $\emptyset'$ to the available $\emptyset'$ is useful to assess the assumed position and direction of the "line of thrust" within the riverbank.

Typical effective "peak" shear strength values of $c' = 2$ psi and $\emptyset' = 16^{\circ}$ were assumed to exist along the vertical sides of the slices. As shown by Figure 13, the rigorous Janbu equations calculated the vertical inter-slice forces to be equal to zero. This was due to the initial assumption that the "line of thrust" acted solely in a horizontal direction. Therefore no shear strength was required on the vertical sides of the slices. Since a c' of 2 p.s.i. and a $\emptyset'$ of 16° was available it was assumed that the calculated Factor of Safety was underestimated.

A more rigorous Janbu method of analysis was required to enable the thrust line to be modified, as shown in Figure 14, such that the interslice forces had horizontal and vertical components. The initial position of the thrust line was selected to allow the interslice forces to act approximately 1/3 of the way up the slice to prevent the development of a tension zone on the soil column. The resulting factor of safety of 2.77 was much greater than the previous analysis even though the same soil shear strength parameters and piezometric conditions prevailed. The plot of the magnitude of the interslice forces in Figure 14 again revealed a stress concentration. Figure 14 revealed that the required ϕ' greatly exceeded the available ϕ' at the implied zone of stress concentration. Therefore the assumption that the thrust line acted in the direction as shown in Figure 14 was incorrect and implied that the resulting Factor of Safety was also in error. The large calculated factor of safety was misleading as an excessive stress concentration implied a state of inequilibrium.

Figures 15 to 17, inclusive, are the results of further analyses in an attempt to obtain a realistic factor of safety such that the final position and geometry of the slip surface and the thrust line yield a solution with a realistic $\phi'_{req'd}$ on the vertical sides of the slices.

The first modification made to the rough Sliding Block assumption was the smoothing of the slip surface at the transition zones between the neutral block and the active and passive wedges. A factor of safety of 1.18 was obtained. This compared very closely to the previous analysis with the horizontal inter-slice force assumption. The analysis of Figure 17 gave a factor of safety of 1.43 with the positioning of the thrust line at the lower 1/3 point of the slice. A horizontal thrust line was assumed near the top of the slope as it was assumed that the soil near the surface was not capable of sustaining vertical inter-slice forces due to the existence of tension cracks. The resulting factor of safety was slightly on the high side due to the relatively high required ϕ' on the vertical sides of the slices for a portion of the slip surface.

The trial analysis of Figure 18 is analogous to that of Figure 17 except that the effective angle of shearing resistance was reduced

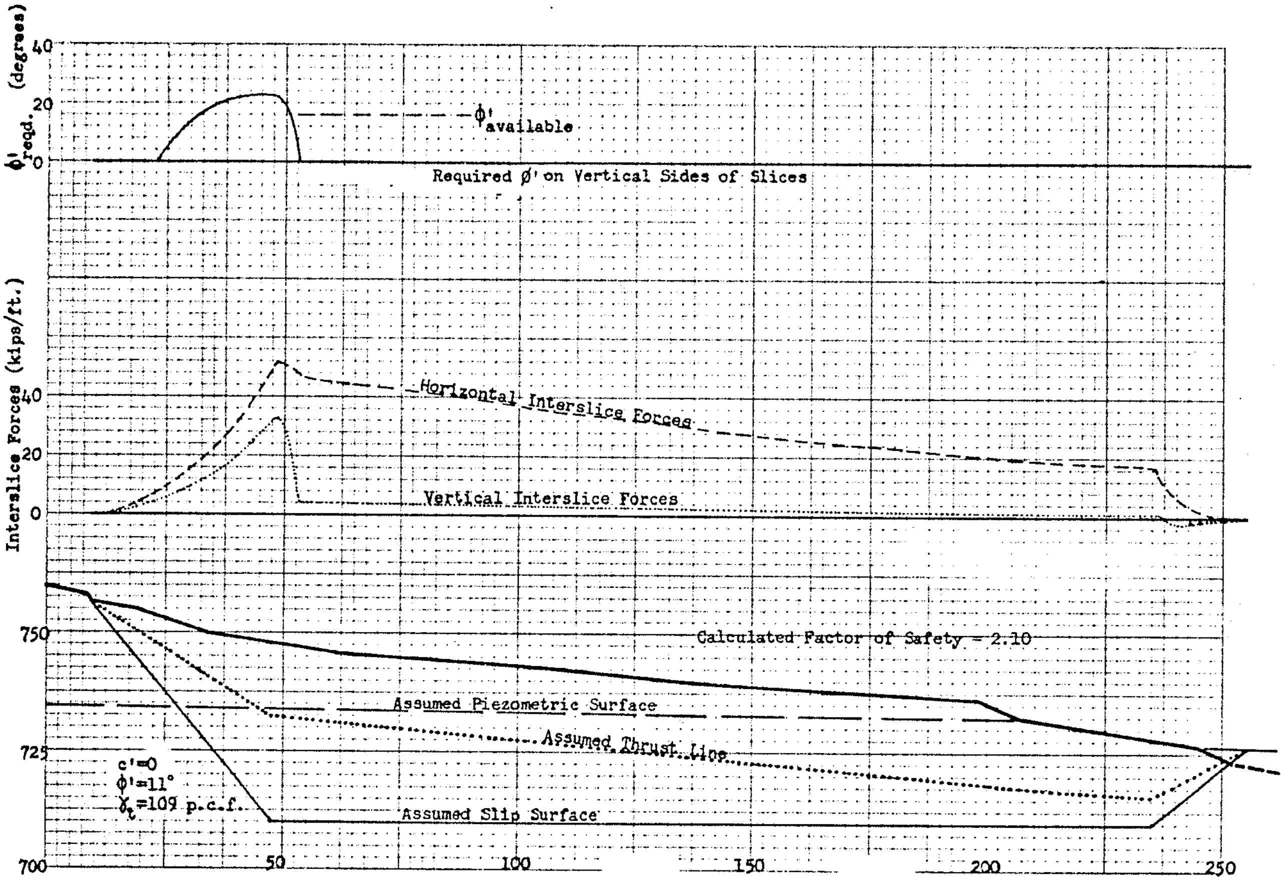


Figure 15: Analysis With Second Modification of Thrust Line

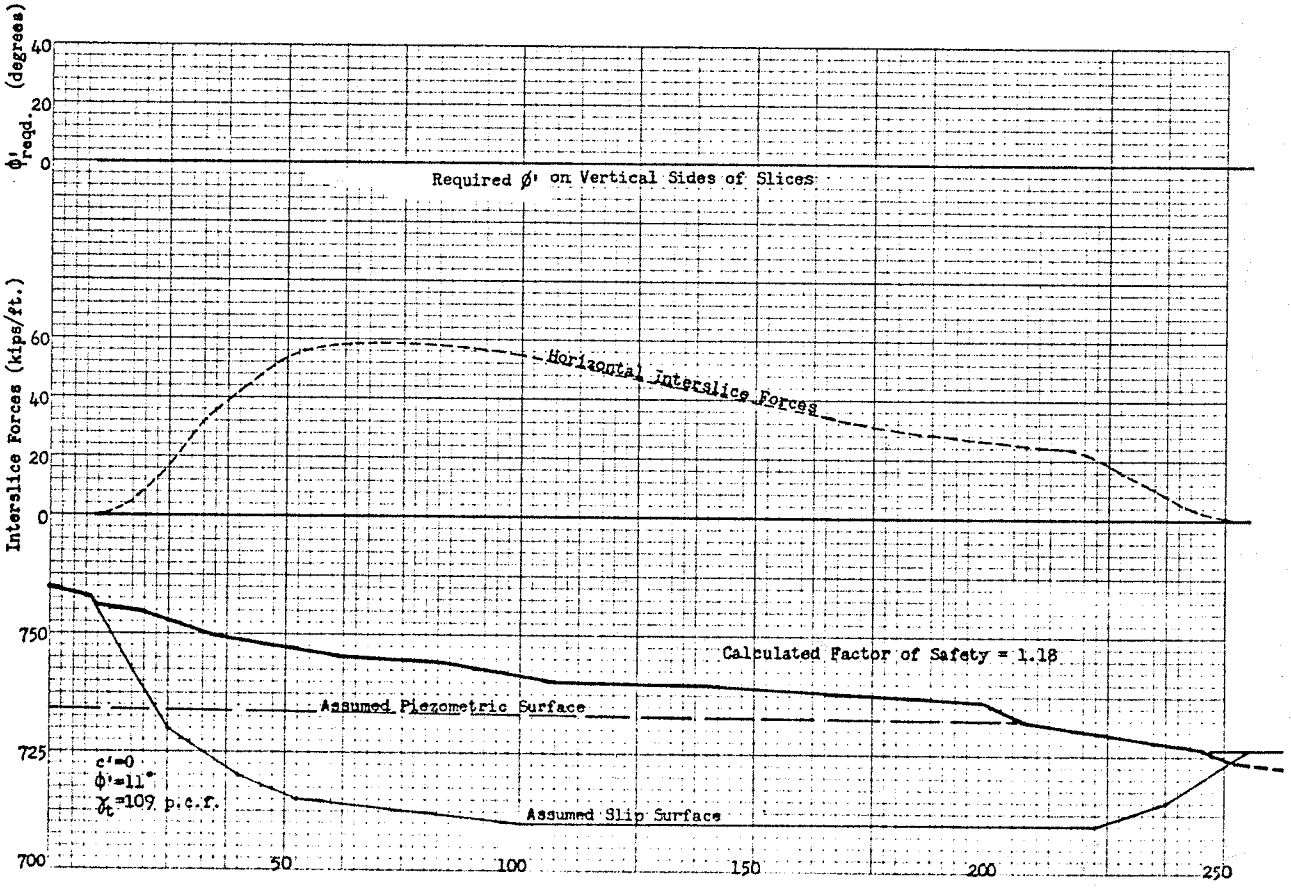


Figure 16: Analysis With Initial Modification of Slip Surface

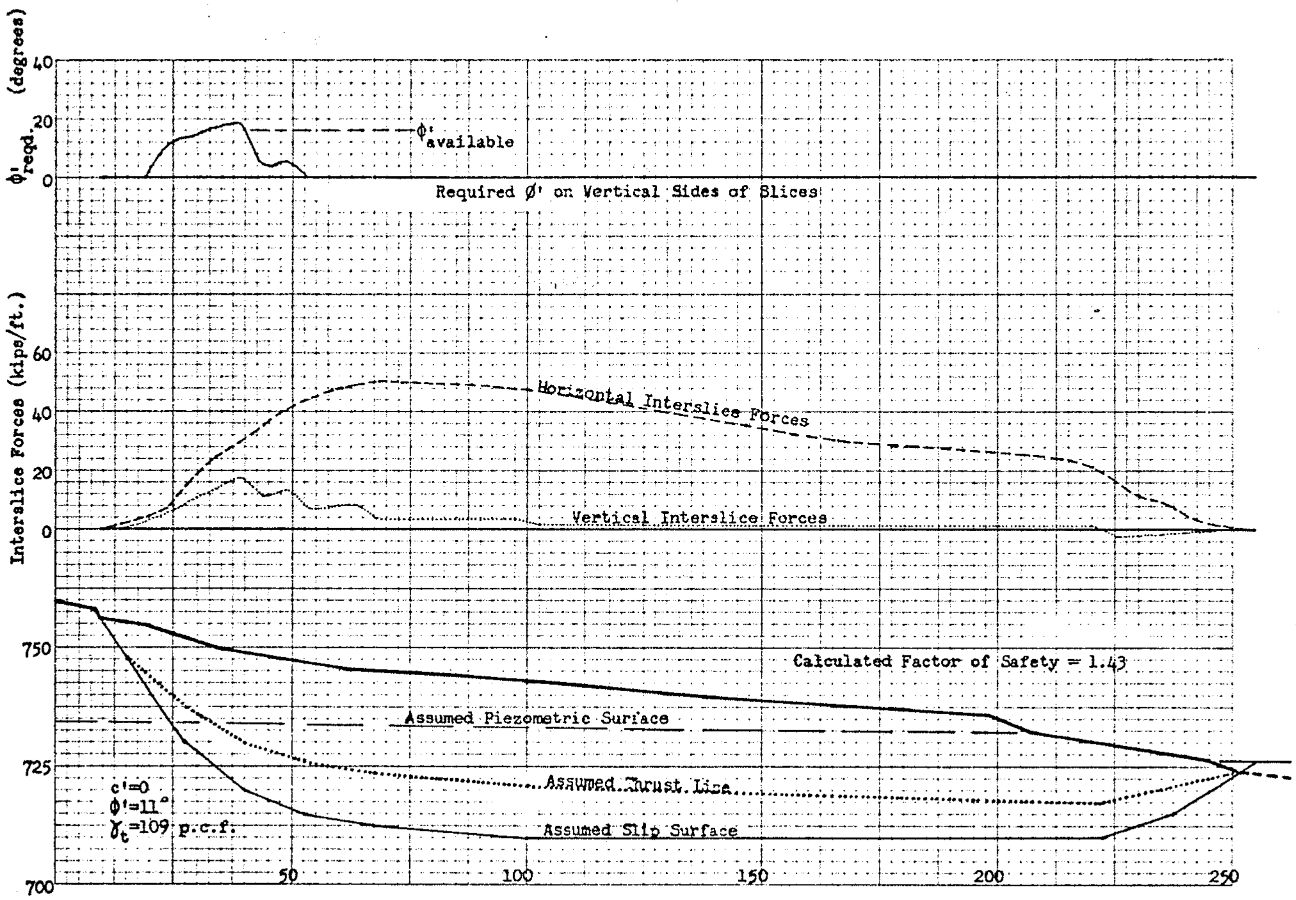


Figure 17: Analysis With Modified Slip Surface and Thrust Line

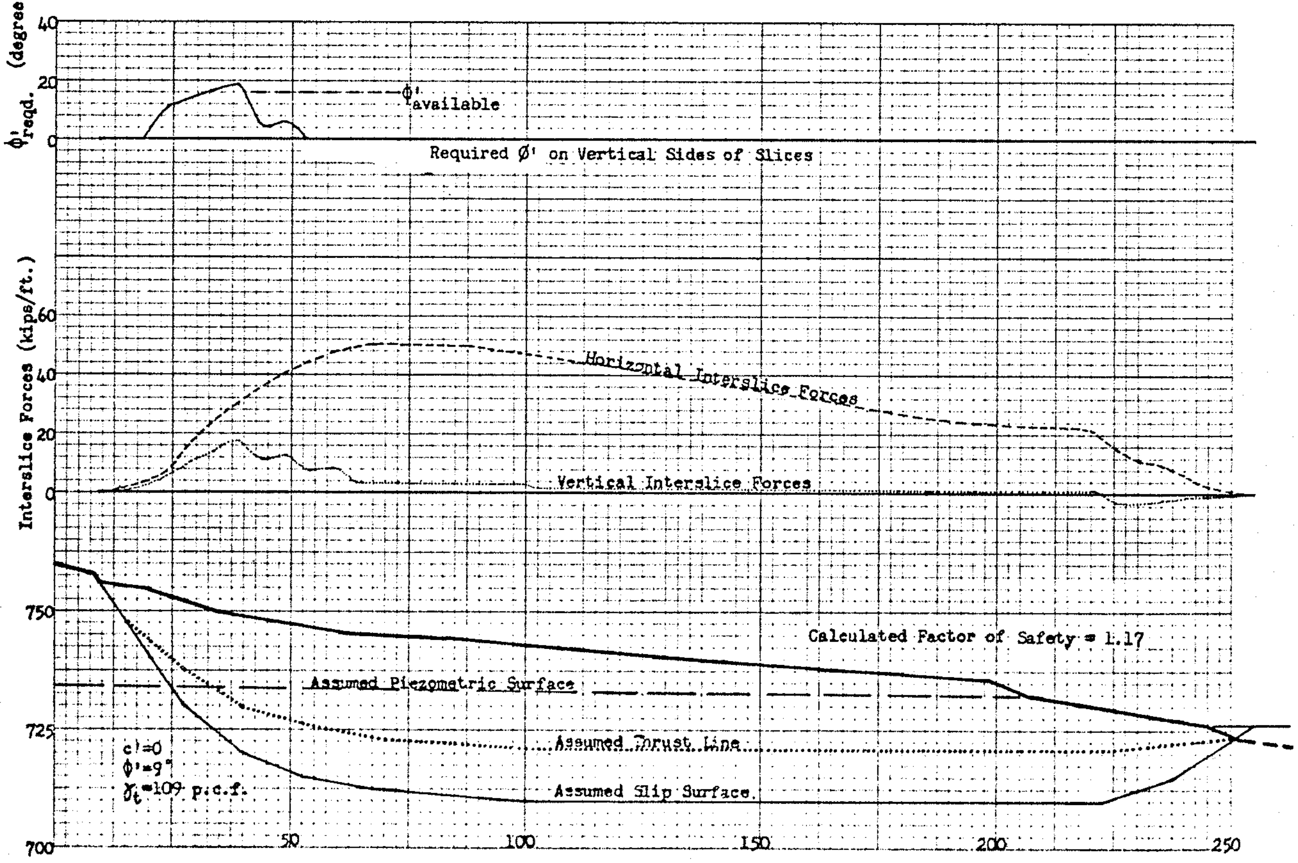


Figure 18: Analysis With Lower Shear Strength Parameters

from 11° to 9°. The factor of safety was reduced from 1.43 to 1.17. The effect of employing shear strength parameters approaching "Peak" values, as in Figure 19, was to drastically increase the factor of safety to 2.65.

The final result using the rigorous Janbu method is illustrated in figure 20 where:

1. Effective "residual" shear strength parameters of $c' = 0$ and $\phi' = 11^\circ$ were assigned to the soil in the region of the slip surface.
2. Effective "Peak" shear strength parameters of $c' = 2$ psi and $\phi' = 16^\circ$ were assigned to the portions of the clay layers not in the slip surface zone.
3. The piezometric condition was that of the assumed critical case.
4. The slip surface was that of the modified Sliding Block assumption and is in accordance with field observations.
5. The thrust line was in a position as determined by trial and error. Its resulting characteristics were primarily as follows:
    a) Vertical location slightly above the lower 1/3 coordinate due to the capability of a clay with an effective cohesion of 2 p.s.i. to sustain some tension.
    b) At the top of the section tension cracks were assumed to exist to the 10 ft. depth; therefore vertical components of interslice forces in this zone were set equal to zero.

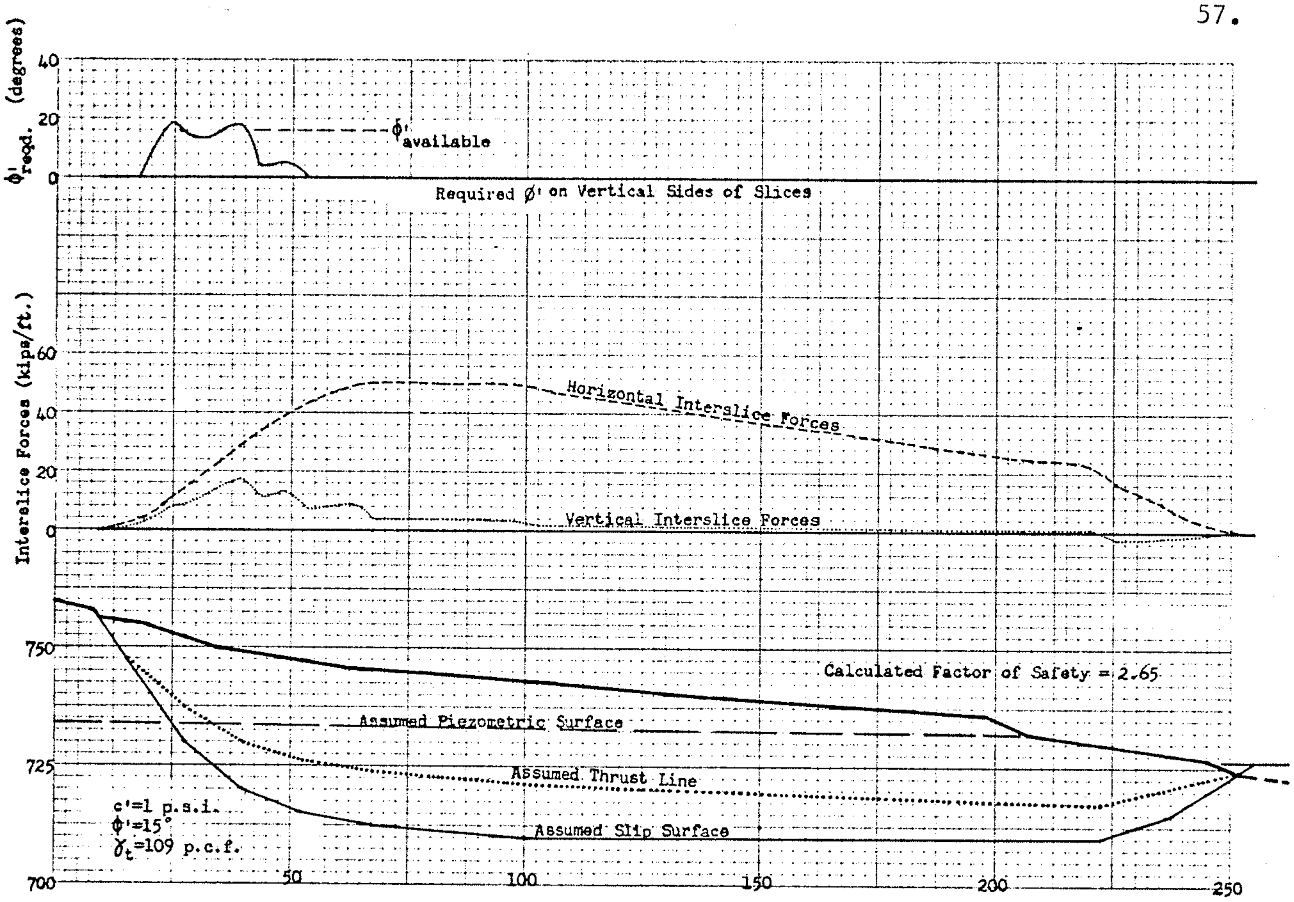


Figure 19: Analysis With "Peak" Shear Strength Parameters

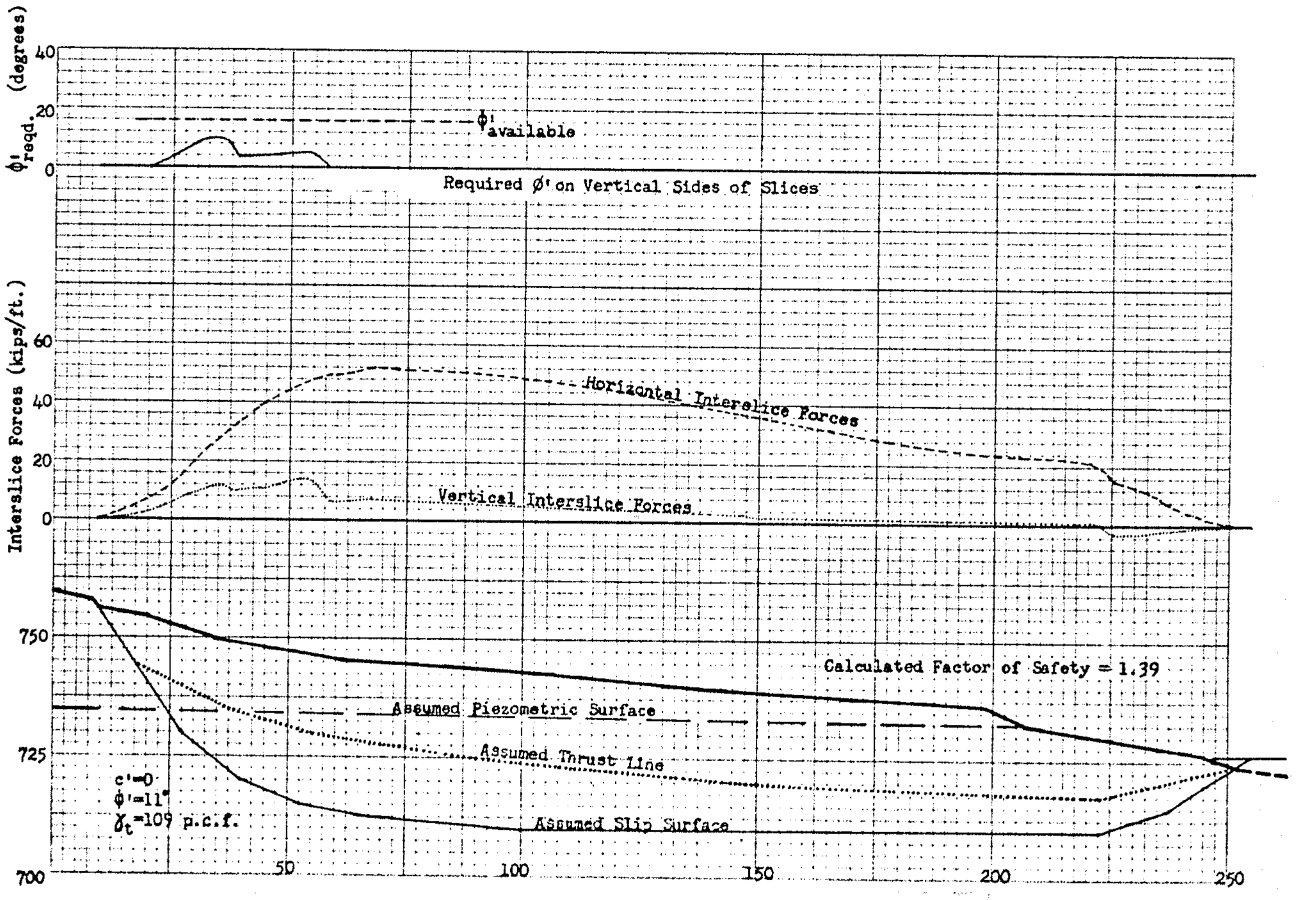


Figure 20: Final Analysis by Rigorous Janbu Method

6. A total statical equilibrium condition was evolved as the required ϕ' along the vertical sides of the slices was appreciably less than the available 16°.

7. The resulting factor of safety for the stability of the riverbank was 1.39.

Note: The initial sliding block approximation with the horizontal inter-slice force assumption resulted in a factor of safety of 1.12 which is conservative by 20%.

Theoretically the more correct solution should be that of the rigorous Janbu method which gave a factor of safety of 1.39. But as the riverbank was in a state of movement, a safety factor of unity should have been obtained. This indicates that the effective residual shear strength parameters used in the analysis were higher than those available in the actual slip surface.

Two further analyses in Figure 20 and 21 reveal the effect of various piezometric surfaces. These illustrate the effect of the piezometric level within the riverbank. A low phreatic surface gave a factor of safety of 1.64, and a higher phreatic surface gave a lower safety factor of 1.23.

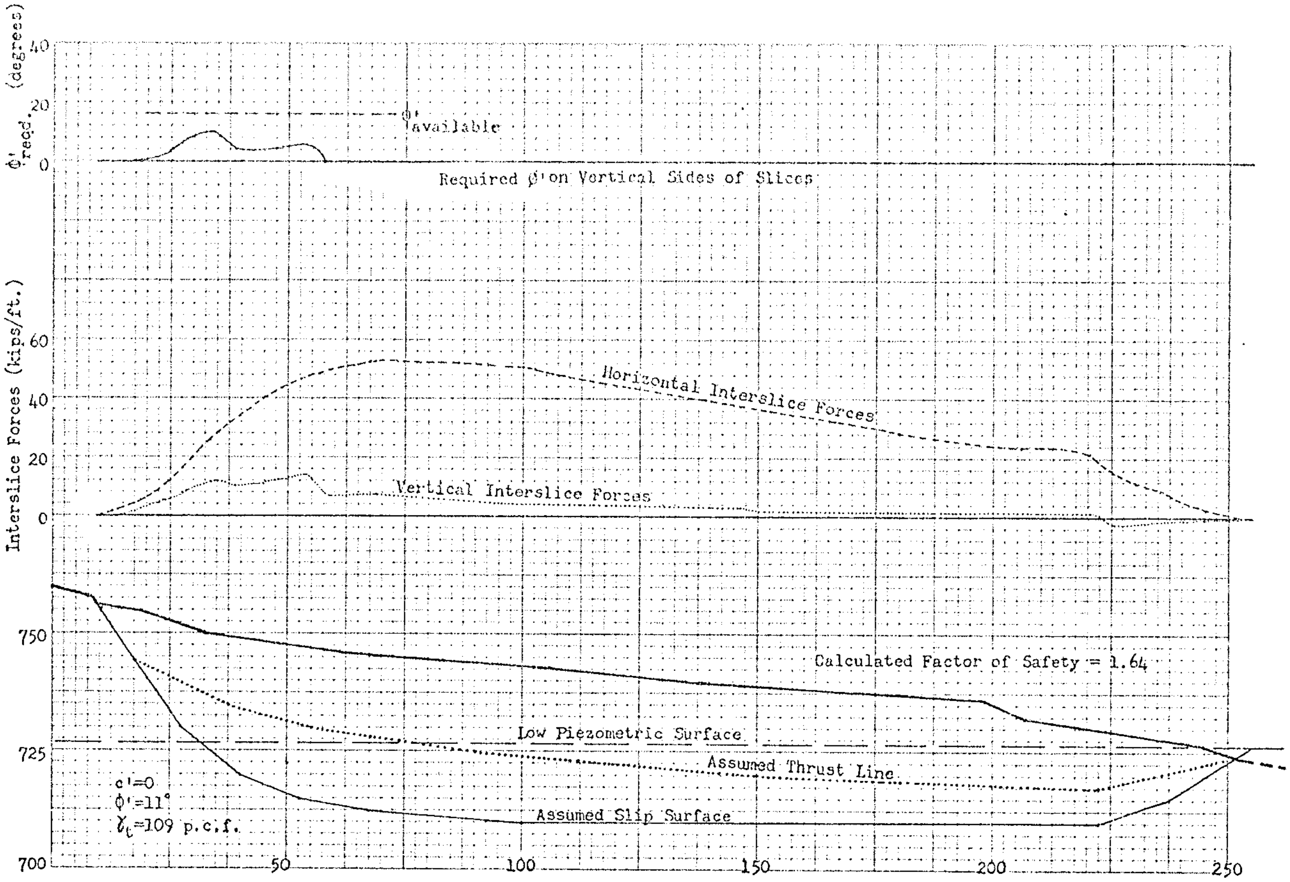


Figure 21: ANALYSIS WITH LOWER PIEZOMETRIC SURFACE

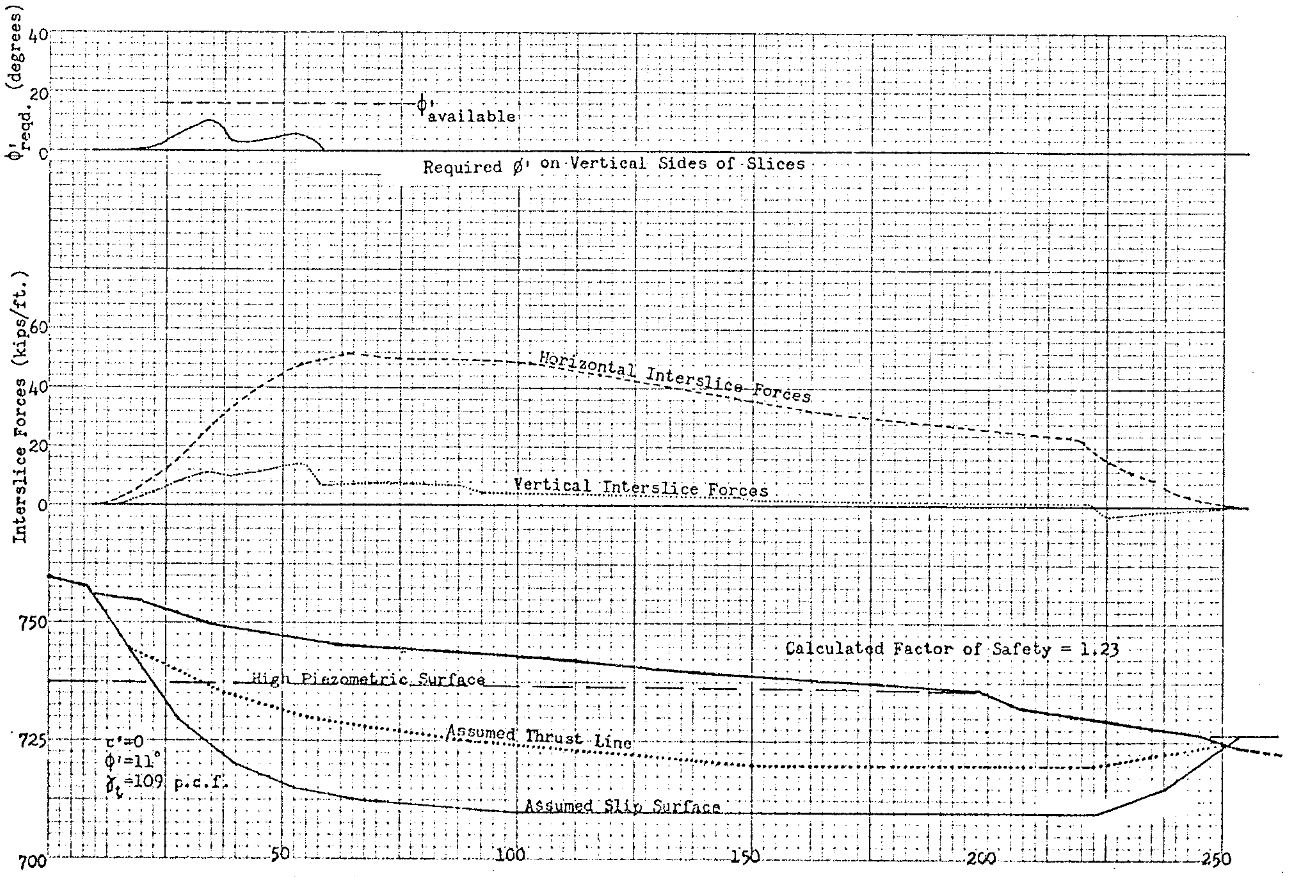


Figure 22: ANALYSIS WITH HIGHER PIEZOMETRIC SURFACE

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

The initial evaluation of the well-point equipped pneumatic piezometers is as follows:

1. The installation process is simple and quick as it eliminates the tedius and time-consuming effort required for the piezometer installations which require backfill.

2. The pneumatic system allows the lines of a set of piezometers to be terminated at one central location.

3. This central read-out location can be positioned where it is not vulnerable to flooding. Inundation was a major problem with the Casagrande piezometers at the St. Vital site.

4. The measuring procedure is a simple operation as the light portable control case can easily be carried to the piezometer installations.

5. The air system eliminates the freezing of the lines.

6. The non-displacement feature of the staff diaphragm within the piezometer unit eliminates time lag which is so evident of the regular Casagrande type piezometer in the relatively impervious clay.

At their location, the two installed "slope indicators" clearly established the position of the failure plane. Furthermore, the "slope indicator" data was precise enough to determine a rate of riverbank movement.

The riverbank has a fully developed failure or slip plane as it had experienced a slope failure and was then partly stabilized. The "slope indicators" indicated that the riverbank is still moving at a slow rate and that the failure zone is largely in the clay layer immediately above the clay-glacial till interface. Recognizing the relative gentle slope, the position of the slip zone, and the location of the main scarp, it then follows that the riverbank is undergoing a predominantly lateral motion as opposed to a rotational slip failure. The best shape approximation of the slip zone or surface is that defined by a three block sliding system. The slip surface underlying the upper active block commences at the main scarp and the slip surface underlying the passive block terminates near the toe of the slope. The slip surface underlying the neutral block is in the nearly horizontal clay layer immediately above the clay-glacial till interface.

Initial porewater pressure readings from the pneumatic piezometers indicated the following:

a) In the period from November, 1968, to the beginning of April, 1969, the major component of the hydraulic gradient within the riverbank was downward. There also appeared to be a minor horizontal flow pattern to the river.

b) During the Spring flood period (April and May, 1969) the major seepage flow was from the river downward into the underlying glacial till layer.

During the flooding period of April and May of 1969, the river level rose only to a Geodetic elevation of 746 feet and stayed at this level for only ten days. In previous years the level of the river has crested at elevations as high as 759 feet and then remained near this level for several weeks. Therefore the porewater pressures developed in this period were assumed to be not as high as were developed during the major floods of previous years.

The assumptions of a circular arc slip surface in both the Fellenius and Simplified Bishop's methods was shown to be at very best, a crude approximation. These methods, employing the measured porewater pressures, and typical effective residual shear strength parameters for Winnipeg clays, gave safety factors in excess of unity, although movement was taking place. The Fellenius Method gave a Factor of Safety of 1.2 and the Simplified Bishop's Method gave a Factor of Safety of 1.3.

The Janbu Method which may be considered to be a superior analysis due to its capability of accomodating more closely the observed shape and position of the slip surface, also did not give safety factors equal to or less than unity when movement was observed. The rigorous Janbu method (Figure 20) yielded a safety factor of 1.39. The simplified version of this method (Figure 13) gave a safety factor of 1.12.

In summary, four different analysis produced safety factors ranging from 1.12 to 1.39, using identical soil strength parameters and porewater pressure conditions for a case where the safety factor should be equal to or less than one. The discrepancy could be explained if the soil strength parameters were over-estimated. However it may also reflect that the methods of analysis are not that exact to produce a better correlation. Although the porewater pressures were carefully measured, it can be argued that had more piezometers been precisely located on the slip surface, higher porewater pressures might have been recorded and a better correlation produced.

7.2 RECOMMENDATIONS

Potential research projects and recommendations resulting from this investigation at the St. Vital riverbank site are as follows:

1. Continued monitoring of the pneumatic piezometers is required to determine additional porewater pressure conditions within the riverbanks. A longer period of measurement is required to confidently establish critical piezometric periods. Additional riverbanks should be instrumented to establish a pattern in the Winnipeg area.
2. At least three to four "slope indicators", strategically located, are required at a site to accurately locate and determine the shape of the slip surface.
3. Additional drained direct shear tests are required at the St. Vital site to determine the actual effective residual shear strength parameters for the soil within the failure zone.
4. An investigation should be undertaken to correlate the position of the piezometric surface of the Upper Carbonate aquifer to the piezometric surfaces within the overlying lacustrine deposits, particularly at the clay-till interface. It is possible that the Upper Carbonate aquifer and the clay-glacial till interface have contact through fissures in the dolomitic limestone bedrock and cemented glacial till. The present low piezometric surface in the Upper Carbonate aquifer in the Central Winnipeg area and the downward hydraulic gradient in the riverbank at the St. Vital

site strongly indicates that there could be a correlation.

5. A major advancement in the analytical process would be to modify the included Slope Stability Computer Program to render it compatible to a cathode-ray-tube display unit. This unit or scope could then portray the geometry of the slope to the engineer. By employing a pen light the engineer would have direct man-machine communications which would allow him to quickly modify the geometry, design, shear strength parameters, porewater pressure factors, and boundary conditions as dictated by his technical criteria, knowledge, logical intuition, and the computed results of the preceding assumptions.

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APPENDIX "A"

"USER'S MANUAL"

for the

Computer Program

"SLOPO"

(SLOPE STABILITY PROGRAM)

SLOPE STABILITY PROGRAM - SLOPO

A-1 INTRODUCTION

The Slope Stability Computer Program conducts a slope stability analysis by the Method of Slices technique by either one of the following options:

1. SIMPLIFIED BISHOP'S METHOD OF SLICES
2. FELLENIUS METHOD OF SLICES
3. JANBU METHOD OF SLICES

The geometrics of the ground surface profile, soil layers, water level, and boundary loadings are described by a series of straight lines. Straight lines are also employed to describe the piezometric surface, and for Option 3 straight lines describe the thrust line and the slip surface. 'Material type" numbers are assigned to each line to enable the computer to recognize the function of each line. Except for those lines describing the piezometric surface, thrust line, and non-circular slip surface, the "material-type" describes the material existing immediately above the line. Either "total" or "effective" shear strength parameters can be selected. In the analytical process the section is divided into equal slice widths, the required parameters of each slice are computed, tabulated, and then inserted into the appropriate equation to calculate the "factor of safety".

The computer program is written in G-level FORTRAN language and requires the following input/output devices:

1. Card Reader, and
2. Printer

The program consists of a Main Program with eight supporting subroutines. A general outline with a brief function description of each routine is as follows:

1. SLOPO - Main Program,
    - (a) Initiates and terminates the program.
    - (b) Controls the computational process by directing the subroutines.
2. READR - Subroutine No: 1,
    - (a) Reads in and writes out a major portion of the input data.
3. STEPS - Subroutine No: 2,
    - (a) Automatically re-positions the specified slip circle centre to eight new positions. This automatically accomodates the Factor of Safety calculations for a 3 x 3 grid.
4. RADIS - Subroutine No: 3,
    - (a) Determines the minimum slip circle radius from a specified slip circle center to a particular surface.
5. PROFL - Subroutine No: 4,
    - (a) Determines the two horizontal extremities of the section bound by the circular slip surface.
    - (b) Calculates the lowest vertical position of slip surface.
    - (c) Calculates slice width.
6. SLICE - Subroutine No: 5,
    - (a) Determines the horizontal co-ordinate for the midpoint of each slice.

(b) Calculates all the geometrical and physical properties required for each slice.

7. BISH - Subroutine No: 6,

Contains the equations to calculate the Factors of Safety by the following Method of Slices techniques:

(a) Simplified Bishop's Method.

(b) Fellenius Method.

8. JANPA - Subroutine No: 8,

Functions are as per the combined functions of Subroutines No: 4 and No: 5, but are related to the non-circular slip surface analysis.

9. JANCA - Subroutine No: 9,

(a) Contains the equations to calculate the Factor of Safety by the non-circular slip surface method of slices technique.

(b) Calculates ϕ' required along the vertical sides of the slices to determine the validity of the directional approximation for the thrust line.

A-2. THEORY

The derivations of the equations employed to calculate the Factors of Safety are as previously discussed in Chapter 5. The resulting equations applicable for each method are as listed below:

1. Fellenius Method of Slices,

$$F = \frac{1}{\sum W \sin\alpha} \sum\left[c'b \sec\alpha + (W \cos\alpha - ub \sec\alpha) \tan\phi'\right] ,$$

2. Simplified Bishop's Method of Slices,

$$F = \frac{1}{\sum W \sin\alpha} \sum\left[\left(c'b + \tan\phi' (W-ub)\right) \frac{\sec\alpha}{1 + \frac{\tan\phi'}{F} \tan\alpha}\right] .$$

This equation is re-iterated until the F values on the left and right hand sides of the equation differ by 0.001 or less.

3. Janbu Method of Slices,

Step 1: Initial Factor of Safety

$$F_o = \frac{\sum(c'b + (W-ub)\tan\phi')}{\sum W \tan\alpha}\left[\frac{1}{N_\alpha}\right] = \frac{\sum A_o}{\sum B_o}$$

where: $N_\alpha = \cos^2\alpha\,(1 + \tan\alpha\frac{\tan\phi'}{F})$

Step 2: Calculation of Vertical Interslice Forces,

$$V_{n+1} = \tan\alpha_t \sum_{o}^{n} (B - \frac{A}{F})$$

Step 3: Modified Factor of Safety,

$$F = \frac{\sum\left[c'b + \left[W-(V_{n+1} - V_n)-U\right] \tan\phi'\right]\frac{1}{N_\alpha}}{\sum\left[W - (V_{n+1} - V_n)\right] \tan\alpha} = \frac{\sum A}{\sum B}$$

Note: Steps 1 and 2 are repeated until the F values on both sides of the equation differ by 0.001 or less.

As per Chapter 6 the following equation calculates ϕ' required along the vertical sides of the slices to indicate if equilibrium can prevail due to the assumed position and direction of the thrust line.

$$\tan\phi'_{req'd} = \frac{V_{n+1} - c'd}{H_{n+1}}$$

Description of above symbols:

W - total weight of slice,

u - porewater pressure at base of slice,

b - width of slice,

d - depth of slice,

c' - cohesion in terms of effective stress,

ϕ' - angle of shearing resistance in terms of effective stress,

H_n - horizontal interslice force,

V_n - vertical interslice force,

α - angle between the base of the slice to the horizontal,

α_t - angle between thrust line and horizontal.

A-3. ASSUMPTIONS AND LIMITATIONS

(1) Geometric Description

Other than for the circular arc slip surface the geometrics of the slope or embankment are described by a series of straight lines. The prime considerations are:

1. The co-ordinates of the end-points of the straight lines must be in accordance with the rectangular Cartesian co-ordinate system.
2. The entire system must exist in the two positive ordinate quadrants (ie. negative Y- axis values will not be accepted).
3. The X_1 co-ordinate of a straight line must always be less than the X_2 co-ordinate. Vertical lines will not be accepted as the tangent of 90^o is infinity. Therefore to insure computational accuracy the maximum slope of a line should be limited to 1 horizontally in 500 vertically.
4. The computational process is such that the section is divided into slices of equal width. Furthermore the geometrical and physical parameters of each slice are referenced from the horizontal mid-point of the slice.

(2) Material Descriptions

The "material type" number for a line defines the type of material above that line. This does not apply to the lines which describe piezometric surface, slip surface or thrust line. For the latter cases the function of the material type number is to merely inform the computer of the purpose for that particular line.

(3) Porewater Pressure Considerations

The porewater pressure domain of an embankment can be described by means of a piezometric surface and/or, porewater pressure parameters.

a. Piezometric Surface

The piezometric surface is defined by a series of straight lines and can represent a top flow line or other surface to approximate the porewater pressure regime. Since only one piezometric surface can be inserted for a particular analysis, the selected surface should depict the piezometric condition for the area of greatest importance in that particular analysis.

The computed unit porewater pressure for a particular slice is equivalent to the height of water from the piezometric surface to the base of the slice. Implied negative pressures are set equal to zero.

b. Porewater Pressure Parameters

The porewater pressure parameter is defined as the ratio of the porewater pressure to the total overburden at the base of the slice; ie. $r_u = u/Wd$. Each soil layer or zone is assigned a factor. Therefore by judicously dividing the section into layers and/or zones and by assigning appropriate porewater pressure factors, and if necessary, inserting a piezometric surface it should be possible to simulate almost every possible porewater pressure condition.

Note: Negative porewater pressures will be considered if negative factors are inserted.

c. Water Surface

If the unit weight of water is given the exact value of 62.4 p.c.f. the unit porewater pressure at the base of the slice will be equal to the height of water from the base to the water surface. Normally a piezometric surface should not be inserted in the same horizontal range as a water surface unless a special piezometric simulation is attempted.

A-4 CAPACITY

The volume of data input is limited as per the Dimension statements within the following routines:

SLOPO - Mainpgm

PROFL

SLICE

JANPA

JANCA

The capacity of the program as per the Source Listing on page 105 is as follows:

An infinite number of problems can be processed at one time.

For each particular problem the following limitations apply:

(a) Maximum Number of Lines = 100.

(b) Maximum Number of Material Types = 20.

(c) Maximum Number of Slices = 100.

(d) Maximum Number of Specified Slip Circle Centers = 50.

To increase or reduce the capacity as per the attached "Source

Listing" implies the modification of the appropriate Dimension Statements for the routines listed above.

A-5 INPUT AND OUTPUT DESCRIPTION

Refer to the section titled "Input Data Card Format" which is contained within the "Mainpgm" on page 106. This section fully describes the set-up and format under which the data must be presented and also provides comments with each variable to aid the user. The above data is entered on the two standard "Slope Stability Data Input" sheets as illustrated in the three examples on pages79 - 84. Finally, refer to page 78 for an illustration of a typical input data deck setup.

Refer to pages 85 - 104 for three typical examples of "Printed Output". These three examples are part of the analysis as conducted in Chapter 6. A general outline of the output is as follows:

1. A listing of the "Input Data".
2. A listing of the results for the circular arc slip surface analysis is as follows:
    a) Co-ordinates of circle center,
    b) Radius of circle center,
    c) Ground surface intersection with slip circle,
    d) Low point of slip circle,
    e) Factors of Safety.

Note: Asterisks indicate either that one of the two methods was not requested or that the input data is incorrect.

3. A listing of the results for the non-circular slip surface analysis is as follows:
    a) Iteration number,

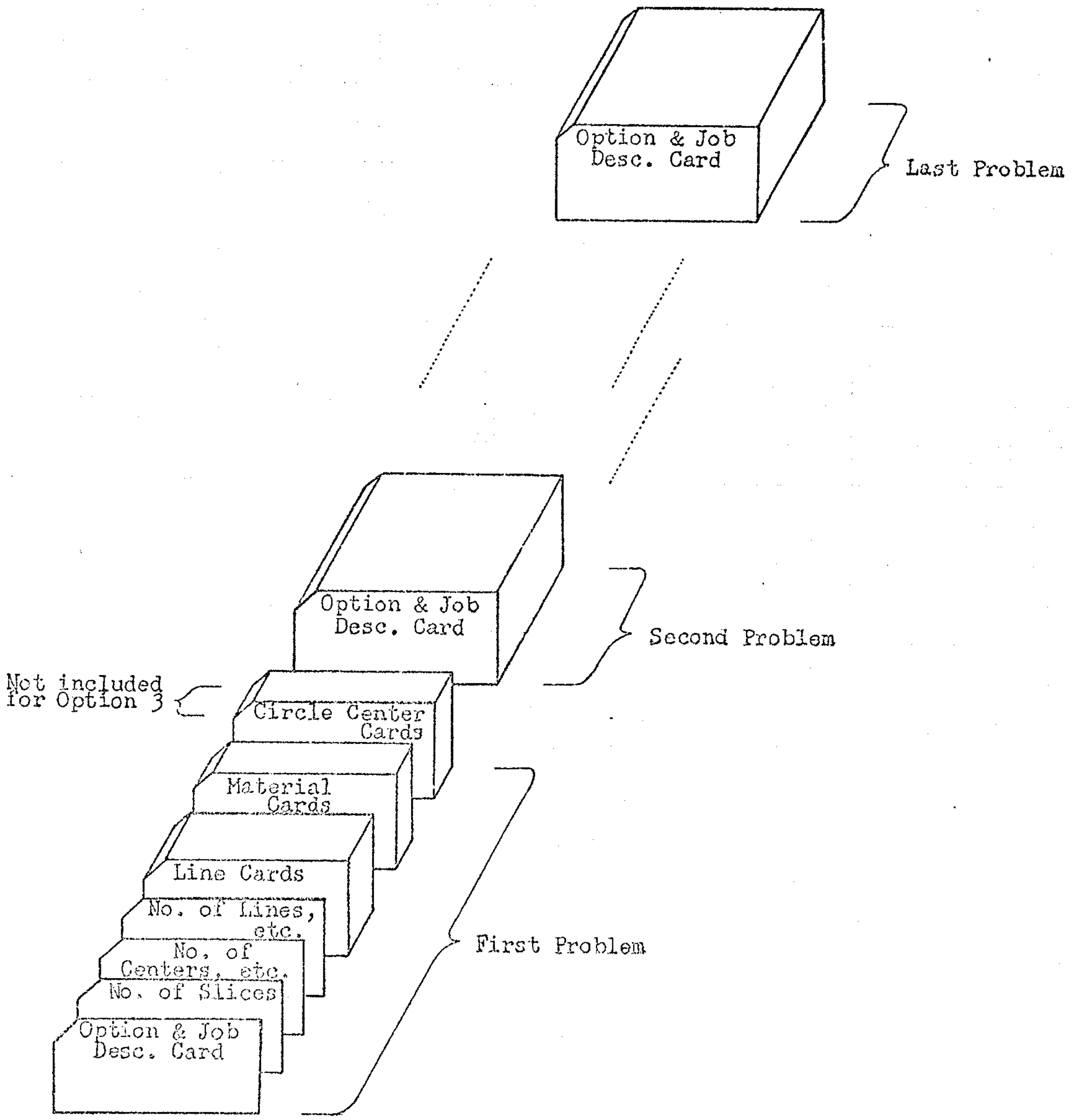
b) Slice number,

c) Horizontal interslice force component on the downward side of designated slice,

d) Corresponding vertical interslice force component,

e) Required ϕ' along the vertical downward side of the designated slice,

f) Horizontal position of downward side of slice.



INPUT DATA DECK SETUP

SLOPE STABILITY DATA INPUT Nº: 1

A	B	C	JOB DESCRIPTION
1	1		BISHOP'S AND SIMPLIFIED METHOD'S NOV.70

Nº OF SLICES: 50.

A=1 : BISHOP'S METHOD
B=1 : SIMPLIFIED METHOD
C=1 : JANBU METHOD

Nº OF CENTERS	Nº OF RAD. TESTS	RADIUS DECREMENT	CENTER INCREMENT
15	1	.	25.

Nº OF LINES	Nº OF TYPES	C	D
22	6	2	1

C = Nº OF LINES TO DESCRIBE PHREATIC SURFACE.
D = 1, IF PHREATIC SURFACE INSERTED.

INSERT DATA LINE CARDS (FROM SHEET DATA INPUT Nº 2) HERE:

TYPE Nº	MATERIAL DESCRIPTION	COHESION (psi)	φ (degrees)	UNIT WT. (p.c.f)	r_u
1	ATMOSPHERE				
2	WATER			62.4	
3					
4					
5	CLAY (RESIDUAL)		11.	109.	
6	PHREATIC SURFACE				

X – CO-ORDINATE OF CIRCLE	Y – CO-ORDINATE OF CIRCLE	RADIUS (ft.)
75.	775.	.
75.	850.	.
75.	925.	.
75.	1000.	.
75.	1075.	.
150.	775.	.
150.	850.	.
150.	925.	.
150.	1000.	.
150.	1075.	.
225.	775.	.
225.	850.	.
225.	925.	.
225.	1000.	.
225.	1075.	.

SHEET 1 OF 2

SLOPE STABILITY DATA INPUT Nº: 2

LINE Nº:	X-1 CO-ORDINATE	Y-1 CO-ORDINATE	X-2 CO-ORDINATE	Y-2 CO-ORDINATE	TYPE Nº:
1	0.	759.8	8.	757.7	1
2	8.	757.7	9.	756.4	1
3	9.	756.4	19.	754.8	1
4	19.	754.8	34.	749.9	1
5	34.	749.9	62.	745.6	1
6	62.	745.6	83.	744.2	1
7	83.	744.2	107.	742.7	1
8	107.	742.7	138.	739.8	1
9	138.	739.8	198.	736.1	1
10	198.	736.1	207.	732.3	1
11	207.	732.3	245.	726.5	1
12	245.	726.5	1000.	726.5	1
13	245.	726.5	252.	723.	2
14	252.	723.	500.	716.	2
15	0.	0.	0.	0.	4
16	0.	0.	0.	0.	4
17	-1000.	708.	1000.	708.	5
18	-1000.	759.8	0.	759.8	1
19	0.	0.	0.	0.	4
20	0.	0.	0.	0.	4
21	-1000.	735.	207.	732.3	6
22	207.	732.3	245.	726.5	6

NOTES: 1. NO VERTICAL LINES. 2. X-1 < X-2.

SHEET 2 OF 2

SLOPE STABILITY DATA INPUT Nº: 1

A	B	C	JOB DESCRIPTION
		1	JANBU METHOD - INITIAL SLIP SURFACE ANALYSIS

Nº OF SLICES: 50.

A=1 : BISHOP'S METHOD
B=1 : SIMPLIFIED METHOD
C=1 : JANBU METHOD

Nº OF CENTERS	Nº OF RAD. TESTS	RADIUS DECREMENT	CENTER INCREMENT
0		.	.

Nº OF LINES	Nº OF TYPES	C	D
22	6	2	1

C = Nº OF LINES TO DESCRIBE PHREATIC SURFACE.
D = 1, IF PHREATIC SURFACE INSERTED.

INSERT DATA LINE CARDS (FROM SHEET DATA INPUT Nº 2) HERE:

TYPE Nº	MATERIAL DESCRIPTION	COHESION (psi)	ø (degrees)	UNIT WT. (p.c.f)	r_u
1	ATMOSPHERE				
2	WATER			62.4	
3	CLAY		11	109.	
4	SLIP SURFACE				
5	THRUST LINE				
6	PHREATIC SURFACE				

X- CO-ORDINATE OF CIRCLE	Y - CO-ORDINATE OF CIRCLE	RADIUS (ft.)
.	.	.

SHEET 1 OF 2

SLOPE STABILITY DATA INPUT Nº: 2

LINE Nº:	X-1 CO-ORDINATE	Y-1 CO-ORDINATE	X-2 CO-ORDINATE	Y-2 CO-ORDINATE	TYPE Nº:
1	0.	759.8	8.	757.7	1
2	8.	757.7	9.	756.4	1
3	9.	756.4	19.	754.9	1
4	19.	754.8	34.	749.9	1
5	34.	749.9	62.	745.6	1
6	62.	745.6	83.	744.2	1
7	83.	744.2	107.	742.7	1
8	107.	742.7	138.	739.8	1
9	138.	739.8	198.	736.1	1
10	198.	736.1	207.	732.3	1
11	207.	732.3	245.	726.5	1
12	245.	726.5	1000.	726.5	1
13	245.	726.5	252.	723.	2
14	252.	723.	500.	716.	2
15	500.	716.	1000.	716.	2
16	-1000.	759.8	0.	759.8	1
17	-1000.	700.	1000.	700.	3
18	9.	756.4	47.5	710.	4
19	47.5	710.	235.	710.	4
20	235.	710.	255.	726.5	4
21	-1000.	735.	207.	732.3	6
22	207.	732.3	245.	726.5	6

NOTES: 1. NO VERTICAL LINES. 2. X-1 < X-2.

SHEET 2 OF 2

SLOPE STABILITY DATA INPUT Nº: 1

A	B	C	JOB DESCRIPTION
		1	JANBU METHOD - FINAL SLIP SURFACE ANALYSIS

Nº OF SLICES
50.

A=1 : BISHOP'S METHOD
B=1 : SIMPLIFIED METHOD
C=1 : JANBU METHOD

Nº OF CENTERS	Nº OF RAD. TESTS	RADIUS DECREMENT	CENTER INCREMENT
0		.	.

Nº OF LINES	Nº OF TYPES	C	D
32	7	2	1

C = Nº OF LINES TO DESCRIBE PHREATIC SURFACE.
D = 1, IF PHREATIC SURFACE INSERTED.

INSERT DATA LINE CARDS (FROM SHEET DATA INPUT Nº 2) HERE:

TYPE Nº	MATERIAL DESCRIPTION	COHESION (psi)	ø (degrees)	UNIT WT. (p.c.f)	r_u
1	ATMOSPHERE	.	.	.	.
2	WATER	.	.	62.4	.
3	CLAY (PEAK)	2.	16.	109.	.
4	CLAY (RESIDUAL)	.	11.	109.	.
5	SLIP SURFACE	.	.	.	.
6	THRUST LINE	.	.	.	.
7	PHREATIC SURFACE	.	.	.	.

X - CO - ORDINATE OF CIRCLE	Y - CO - ORDINATE OF CIRCLE	RADIUS (ft.)
.	.	.

31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50

SHEET 1 OF 2

SLOPE STABILITY DATA INPUT Nº: 2

LINE Nº:	X-1 CO-ORDINATE	Y-1 CO-ORDINATE	X-2 CO-ORDINATE	Y-2 CO-ORDINATE	TYPE Nº:
1	0.	759.8	8.	757.7	1
2	8.	757.7	9.	756.4	1
3	9.	756.4	19.	754.8	1
4	19.	754.8	34.	749.9	1
5	34.	749.9	62.	745.6	1
6	62.	745.6	83.	744.2	1
7	83.	744.2	107.	742.7	1
8	107.	742.7	138.	739.8	1
9	138.	739.8	198.	736.1	1
10	198.	736.1	207.	732.3	1
11	207.	732.3	245.	726.5	1
12	245.	726.5	1000.	726.5	1
13	-1000.	759.8	0.	759.8	1
14	245.	726.5	252.	723.	2
15	252.	723.	500.	716.	2
16	-1000.	700.	1000.	700.	4
17	9.	756.4	27.5	730.	5
18	27.5	730.	40.	720.	5
19	40.	720.	52.5	715.	5
20	52.5	715.	67.5	712.5	5
21	67.5	712.5	100.	710.	5
22	100.	710.	222.5	710.	5
23	222.5	710.	237.5	715.	5
24	237.5	715.	255.	726.5	5
25	17.5	744.	37.5	735.	6
26	37.5	735.	55.	730.	6
27	55.	730.	90.	725.	6
28	90.	725.	150.	720.	6
29	150.	720.	222.5	717.5	6
30	222.5	717.5	251.	723.	6
31	-1000.	735.	207.	732.3	7
32	207.	732.3	245.	726.5	7
	.	.	.	.	
	.	.	.	.	
	.	.	.	.	
	.	.	.	.	
	.	.	.	.	

NOTES: 1. NO VERTICAL LINES. 2. X-1 < X-2.

SHEET 2 OF 2

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                                            SLOPE STABILITY ANALYSIS
                                                     BY THE
                                           METHOD OF SLICES TECHNIQUE
                                           --------------------------

      JOB DESCRIPTION   --   BISHOP'S AND SIMPLIFIED METHODS          NOV.70   --
                             -----------------------------------------------

                                                   INPUT DATA
                                                   ----------

      NUMBER OF STRAIGHT LINES ARE  22
      NUMBER OF MATERIAL TYPES ARE  6
      NUMBER OF LINES REQUIRED TO DESCRIBE PHREATIC SURFACES ARE  2
      NUMBER OF PHREATIC SURFACES ARE  1
      NUMBER OF SLICES = 50.0

      COORDINATES OF GIVEN STRAIGHT LINES ARE AS FOLLOWS

       NUMBER        X-1 COORDINATE      Y-1 COORDINATE      X-2 COORDINATE      Y-2 COORDINATE        TYPE
          1               0.0               759.800               8.000             757.700              1
          2               8.000             757.700               9.000             756.400              1
          3               9.000             756.400              19.000             754.800              1
          4              19.000             754.800              34.000             749.900              1
          5              34.000             749.900              62.000             745.600              1
          6              62.000             745.600              83.000             744.200              1
          7              83.000             744.200             107.000             742.700              1
          8             107.000             742.700             138.000             739.800              1
          9             138.000             739.800             198.000             736.100              1
         10             198.000             736.100             207.000             732.300              1
         11             207.000             732.300             245.000             726.500              1
         12             245.000             726.500            1000.000             726.500              1
         13             245.000             726.500             252.000             723.000              2
         14             252.000             723.000             500.000             716.000              2
         15               0.0                 0.0                 0.0                 0.0                4
         16               0.0                 0.0                 0.0                 0.0                4
         17           -1000.000             708.000            1000.000             708.000              5
         18           -1000.000             759.800               0.0               759.800              1
         19               0.0                 0.0                 0.0                 0.0                4
         20               0.0                 0.0                 0.0                 0.0                4
         21           -1000.000             735.000             207.000             732.300              6
         22             207.000             732.300             245.000             726.500              6
TYPE       SOIL           EFFECTIVE           EFFECTIVE            TOTAL        PORE PRESSURE
        DESCRIPTION       COHESION          FRICTION ANGLE      UNIT WEIGHT     PARAMETER--RU
   1  ATMOSPHERE            0.0                  0.0                0.0                0.0
   2  WATER                 0.0                  0.0               62.400              0.0
   3                        0.0                  0.0                0.0                0.0
   4                        0.0                  0.0                0.0                0.0
   5  CLAY(RESIDUAL)        0.0                 11.000            109.000              0.0
   6  PHREATIC SURFACE      0.0                  0.0                0.0                0.0
```

CENTER OF FAILURE ARC		RADIUS OF FAILURE ARC	GROUND SURFACE INTERSECTIONS WITH SLIP CIRCLE				LOW POINT OF SLIP CIRCLE		FACTOR OF SAFETY	
X	Y		X	Y	X	Y	X	Y	SIMPLIFIED METHOD	BISHOPS METHOD
75.00	775.00	67.0	10.7	756.1	132.3	740.3	75.0	708.0	1.406	2.035
50.00	775.00	67.0	-15.2	759.8	108.6	742.5	50.0	708.0	1.114	1.627
50.00	800.00	92.0	-32.7	759.8	120.9	741.4	50.0	708.0	1.148	1.495
75.00	800.00	92.0	-7.7	759.8	144.2	739.4	75.0	708.0	1.186	1.555
100.00	800.00	92.0	20.1	754.4	167.9	738.0	100.0	708.0	1.557	2.003
100.00	775.00	67.0	38.2	749.3	156.3	738.7	100.0	708.0	1.819	2.560
100.00	750.00	42.0	58.2	746.2	140.7	739.6	100.0	708.0	2.317	4.044
75.00	750.00	42.0	33.0	750.2	116.2	741.8	75.0	708.0	2.129	3.811
50.00	750.00	42.0	8.6	756.9	91.5	743.7	50.0	708.0	1.455	2.611
75.00	850.00	142.0	-34.7	759.8	162.6	738.3	75.0	708.0	1.185	1.399
50.00	850.00	142.0	-59.7	759.8	139.4	739.7	50.0	708.0	1.271	1.491
50.00	875.00	167.0	-70.9	759.8	147.2	739.2	50.0	708.0	1.331	1.520
75.00	875.00	167.0	-45.9	759.8	170.2	737.8	75.0	708.0	1.223	1.404
100.00	875.00	167.0	-20.9	759.8	193.1	736.4	100.0	708.0	1.231	1.419
100.00	850.00	142.0	-9.7	759.8	185.8	736.9	100.0	708.0	1.253	1.483
100.00	825.00	117.0	3.5	758.9	177.5	737.4	100.0	708.0	1.364	1.670
75.00	825.00	117.0	-22.1	759.8	154.1	738.8	75.0	708.0	1.158	1.426
50.00	825.00	117.0	-47.1	759.8	130.9	740.5	50.0	708.0	1.208	1.475

75.00	925.00	217.0	-65.7	759.8	183.4	737.0	75.0	708.0	1.311	1.452
50.00	925.00	217.0	-90.7	759.8	160.7	738.4	50.0	708.0	1.443	1.593
50.00	950.00	242.0	-99.6	759.8	166.7	738.0	50.0	708.0	1.495	1.631
75.00	950.00	242.0	-74.6	759.8	189.2	736.6	75.0	708.0	1.354	1.482
100.00	950.00	242.0	-49.6	759.8	206.3	732.6	100.0	708.0	1.263	1.385
100.00	925.00	217.0	-40.7	759.8	203.0	734.0	100.0	708.0	1.250	1.388
100.00	900.00	192.0	-31.2	759.8	199.2	735.6	100.0	708.0	1.237	1.397
75.00	900.00	192.0	-56.2	759.8	177.1	737.4	75.0	708.0	1.267	1.425
50.00	900.00	192.0	-81.2	759.8	154.3	738.8	50.0	708.0	1.388	1.555

75.00	1000.00	292.0	-91.0	759.8	199.0	735.7	75.0	708.0	1.437	1.545
50.00	1000.00	292.0	-116.0	759.8	177.6	737.4	50.0	708.0	1.591	1.707
50.00	1025.00	317.0	-123.6	759.8	182.5	737.1	50.0	708.0	1.635	1.743
75.00	1025.00	317.0	-98.6	759.8	201.8	734.5	75.0	708.0	1.473	1.572
100.00	1025.00	317.0	-73.6	759.8	217.7	730.7	100.0	708.0	1.311	1.399
100.00	1000.00	292.0	-66.0	759.8	214.1	731.2	100.0	708.0	1.293	1.389
100.00	975.00	267.0	-58.0	759.8	210.2	731.8	100.0	708.0	1.276	1.384
75.00	975.00	267.0	-83.0	759.8	194.6	736.3	75.0	708.0	1.397	1.514
50.00	975.00	267.0	-108.0	759.8	172.3	737.7	50.0	708.0	1.544	1.669

75.00	1075.00	367.0	-113.0	759.8	206.7	732.4	75.0	708.0	1.529	1.615
50.00	1075.00	367.0	-138.0	759.8	191.7	736.5	50.0	708.0	1.717	1.813
50.00	1100.00	392.0	-144.7	759.8	196.0	736.2	50.0	708.0	1.756	1.847

75.00	1100.00	392.0	-119.7	759.8	209.7	731.9	75.0	708.0	1.552	1.632
100.00	1100.00	392.0	-94.7	759.8	227.2	729.2	100.0	708.0	1.371	1.440
100.00	1075.00	367.0	-88.0	759.8	224.2	729.7	100.0	708.0	1.350	1.425
100.00	1050.00	342.0	-80.9	759.8	221.1	730.2	100.0	708.0	1.329	1.410
75.00	1050.00	342.0	-105.9	759.8	204.4	733.4	75.0	708.0	1.503	1.595
50.00	1050.00	342.0	-130.9	759.8	187.3	736.8	50.0	708.0	1.677	1.779

150.00	775.00	67.0	90.8	743.7	203.0	734.0	150.0	708.0	1.737	2.425
125.00	775.00	67.0	64.9	745.4	180.3	737.2	125.0	708.0	1.872	2.614
125.00	800.00	92.0	49.4	747.5	191.6	736.5	125.0	708.0	1.804	2.290
150.00	800.00	92.0	76.5	744.6	211.5	731.6	150.0	708.0	1.531	1.925
175.00	800.00	92.0	102.8	743.0	232.7	728.4	175.0	708.0	1.106	1.368
175.00	775.00	67.0	116.8	741.8	224.3	729.7	175.0	708.0	1.152	1.565
175.00	750.00	42.0	134.2	740.2	212.7	731.4	175.0	708.0	1.345	2.295
150.00	750.00	42.0	108.7	742.5	189.8	736.6	150.0	708.0	1.975	3.486
125.00	750.00	42.0	83.4	744.2	165.3	738.1	125.0	708.0	1.989	3.483

150.00	850.00	142.0	52.1	747.1	225.1	729.5	150.0	708.0	1.397	1.604
125.00	850.00	142.0	19.9	754.5	205.4	733.0	125.0	708.0	1.537	1.794
125.00	875.00	167.0	5.5	758.4	210.8	731.7	125.0	708.0	1.371	1.565
150.00	875.00	167.0	40.5	748.9	230.5	728.7	150.0	708.0	1.352	1.517
175.00	875.00	167.0	70.1	745.1	251.4	726.5	175.0	708.0	1.116	1.240
175.00	850.00	142.0	80.1	744.4	245.1	726.5	175.0	708.0	1.105	1.256

175.00	825.00	117.0	90.9	743.7	239.4	727.4	175.0	708.0	1.099	1.290
150.00	825.00	117.0	64.2	745.5	218.9	730.5	150.0	708.0	1.448	1.720
125.00	825.00	117.0	35.5	749.7	200.0	735.2	125.0	708.0	1.707	2.058
150.00	925.00	217.0	14.5	755.5	239.5	727.3	150.0	708.0	1.243	1.358
125.00	925.00	217.0	-15.7	759.8	220.6	730.2	125.0	708.0	1.204	1.332
125.00	950.00	242.0	-24.6	759.8	224.9	729.6	125.0	708.0	1.180	1.290
150.00	950.00	242.0	0.6	759.6	243.4	726.7	150.0	708.0	1.181	1.279
175.00	950.00	242.0	40.4	748.9	267.8	726.5	175.0	708.0	1.138	1.218
175.00	925.00	217.0	50.3	747.4	262.6	726.5	175.0	708.0	1.135	1.226
175.00	900.00	192.0	60.6	745.8	257.2	726.5	175.0	708.0	1.128	1.232
150.00	900.00	192.0	27.8	751.9	235.3	728.0	150.0	708.0	1.307	1.443
125.00	900.00	192.0	-6.2	759.8	216.0	730.9	125.0	708.0	1.257	1.411
150.00	1000.00	292.0	-16.0	759.8	252.3	726.5	150.0	708.0	1.114	1.190
125.00	1000.00	292.0	-41.0	759.8	232.3	728.4	125.0	708.0	1.178	1.263
125.00	1025.00	317.0	-48.6	759.8	235.6	727.9	125.0	708.0	1.187	1.264
150.00	1025.00	317.0	-23.6	759.8	256.7	726.5	150.0	708.0	1.107	1.175
175.00	1025.00	317.0	2.3	759.2	281.7	726.5	175.0	708.0	1.102	1.162
175.00	1000.00	292.0	15.6	755.3	277.3	726.5	175.0	708.0	1.122	1.187
175.00	975.00	267.0	28.8	751.6	272.6	726.5	175.0	708.0	1.138	1.211
150.00	975.00	267.0	-8.0	759.8	247.6	726.5	150.0	708.0	1.138	1.224

125.00	975.00	267.0	-33.0	759.8	228.7	729.0	125.0	708.0	1.175	1.271
150.00	1075.00	367.0	-38.0	759.8	265.0	726.5	150.0	708.0	1.111	1.168
125.00	1075.00	367.0	-63.0	759.8	241.6	727.0	125.0	708.0	1.211	1.276
125.00	1100.00	392.0	-69.7	759.8	244.3	726.6	125.0	708.0	1.229	1.289
150.00	1100.00	392.0	-44.7	759.8	269.0	726.5	150.0	708.0	1.122	1.174
175.00	1100.00	392.0	-19.7	759.8	294.0	726.5	175.0	708.0	1.070	1.118
175.00	1075.00	367.0	-13.0	759.8	290.0	726.5	175.0	708.0	1.070	1.122
175.00	1050.00	342.0	-5.9	759.8	285.9	726.5	175.0	708.0	1.080	1.135
150.00	1050.00	342.0	-30.9	759.8	260.9	726.5	150.0	708.0	1.106	1.168
125.00	1050.00	342.0	-55.9	759.8	238.7	727.5	125.0	708.0	1.197	1.268
225.00	775.00	67.0	169.2	737.9	271.2	726.5	225.0	708.0	0.553	0.754
200.00	775.00	67.0	143.2	739.5	246.2	726.5	200.0	708.0	0.764	1.023
200.00	800.00	92.0	129.8	740.6	255.3	726.5	200.0	708.0	0.813	0.991
225.00	800.00	92.0	156.4	738.7	280.3	726.5	225.0	708.0	0.635	0.785
250.00	800.00	92.0	182.9	737.0	305.3	726.5	250.0	708.0	0.647	0.832
250.00	775.00	67.0	195.4	736.3	296.2	726.5	250.0	708.0	0.622	0.895
250.00	750.00	42.0	212.3	731.5	284.8	726.5	250.0	708.0	0.600	1.106
225.00	750.00	42.0	185.1	736.9	259.8	726.5	225.0	708.0	0.451	0.792
200.00	750.00	42.0	159.6	738.5	235.7	727.9	200.0	708.0	0.684	1.154
225.00	850.00	142.0	135.1	740.1	295.1	726.5	225.0	708.0	0.764	0.865

200.00	850.00	142.0	107.0	742.7	270.1	726.5	200.0	708.0	0.880	0.993
200.00	875.00	167.0	97.3	743.3	276.4	726.5	200.0	708.0	0.913	1.009
225.00	875.00	167.0	125.4	741.0	301.4	726.5	225.0	708.0	0.814	0.903
250.00	875.00	167.0	153.3	738.9	326.4	726.5	250.0	708.0	0.789	0.891
250.00	850.00	142.0	162.3	738.3	320.1	726.5	250.0	708.0	0.744	0.862
250.00	825.00	117.0	172.1	737.7	313.1	726.5	250.0	708.0	0.695	0.838
225.00	825.00	117.0	145.3	739.3	288.1	726.5	225.0	708.0	0.705	0.825
200.00	825.00	117.0	117.9	741.7	263.1	726.5	200.0	708.0	0.848	0.985
225.00	925.00	217.0	107.4	742.7	312.6	726.5	225.0	708.0	0.893	0.965
200.00	925.00	217.0	79.7	744.4	287.6	726.5	200.0	708.0	0.977	1.053
200.00	950.00	242.0	71.5	745.0	292.8	726.5	200.0	708.0	1.008	1.076
225.00	950.00	242.0	99.4	743.2	317.8	726.5	225.0	708.0	0.927	0.993
250.00	950.00	242.0	128.6	740.7	342.8	726.5	250.0	708.0	0.907	0.980
250.00	925.00	217.0	136.7	739.9	337.6	726.5	250.0	708.0	0.871	0.951
250.00	900.00	192.0	144.8	739.4	332.2	726.5	250.0	708.0	0.831	0.921
225.00	900.00	192.0	116.2	741.8	307.2	726.5	225.0	708.0	0.855	0.935
200.00	900.00	192.0	88.3	743.9	282.2	726.5	200.0	708.0	0.946	1.030
225.00	1000.00	292.0	84.4	744.1	327.3	726.5	225.0	708.0	0.988	1.044
200.00	1000.00	292.0	54.7	746.7	302.3	726.5	200.0	708.0	1.063	1.121
200.00	1025.00	317.0	45.7	748.1	306.7	726.5	200.0	708.0	1.082	1.136
225.00	1025.00	317.0	77.2	744.6	331.7	726.5	225.0	708.0	1.016	1.069

250.00	1025.00	317.0	105.7	742.8	356.7	726.5	250.0	708.0	0.995	1.051
250.00	1000.00	292.0	113.0	742.1	352.3	726.5	250.0	708.0	0.968	1.029
250.00	975.00	267.0	120.7	741.4	347.6	726.5	250.0	708.0	0.939	1.005
225.00	975.00	267.0	91.7	743.7	322.6	726.5	225.0	708.0	0.958	1.019
200.00	975.00	267.0	63.6	745.5	297.6	726.5	200.0	708.0	1.037	1.099
225.00	1075.00	367.0	63.4	745.5	340.0	726.5	225.0	708.0	1.070	1.117
200.00	1075.00	367.0	23.1	753.5	315.0	726.5	200.0	708.0	1.106	1.153
200.00	1100.00	392.0	12.3	755.9	319.0	726.5	200.0	708.0	1.102	1.147
225.00	1100.00	392.0	55.4	746.6	344.0	726.5	225.0	708.0	1.093	1.137
250.00	1100.00	392.0	85.9	744.0	369.0	726.5	250.0	708.0	1.066	1.113
250.00	1075.00	367.0	92.3	743.6	365.0	726.5	250.0	708.0	1.043	1.093
250.00	1050.00	342.0	98.9	743.2	360.9	726.5	250.0	708.0	1.019	1.072
225.00	1050.00	342.0	70.2	745.1	335.9	726.5	225.0	708.0	1.044	1.093
200.00	1050.00	342.0	36.8	749.5	310.9	726.5	200.0	708.0	1.099	1.149

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                                          SLOPE STABILITY ANALYSIS
                                                   BY THE
                                         METHOD OF SLICES TECHNIQUE
                                         --------------------------

    JOB DESCRIPTION    --    JANBU METHOD - INITIAL SLIP SURFACE ANALYSIS      --
                             ------------------------------------------------

                                                INPUT DATA
                                                ----------

    NUMBER OF STRAIGHT LINES ARE  22
    NUMBER OF MATERIAL TYPES ARE  6
    NUMBER OF LINES REQUIRED TO DESCRIBE PHREATIC SURFACES ARE  2
    NUMBER OF PHREATIC SURFACES ARE  1
    NUMBER OF SLICES = 50.0

    COORDINATES OF GIVEN STRAIGHT LINES ARE AS FOLLOWS

     NUMBER        X-1 COORDINATE      Y-1 COORDINATE      X-2 COORDINATE      Y-2 COORDINATE        TYPE
        1               0.0               759.800               8.000             757.700              1
        2               8.000             757.700               9.000             756.400              1
        3               9.000             756.400              19.000             754.800              1
        4              19.000             754.800              34.000             749.900              1
        5              34.000             749.900              62.000             745.600              1
        6              62.000             745.600              83.000             744.200              1
        7              83.000             744.200             107.000             742.700              1
        8             107.000             742.700             138.000             739.800              1
        9             138.000             739.800             198.000             736.100              1
       10             198.000             736.100             207.000             732.300              1
       11             207.000             732.300             245.000             726.500              1
       12             245.000             726.500            1000.000             726.500              1
       13             245.000             726.500             252.000             723.000              2
       14             252.000             723.000             500.000             716.000              2
       15             500.000             716.000            1000.000             716.000              2
       16           -1000.000             759.800               0.0               759.800              1
       17           -1000.000             700.000            1000.000             700.000              3
       18               9.000             756.400              47.500             710.000              4
       19              47.500             710.000             235.000             710.000              4
       20             235.000             710.000             255.000             726.500              4
       21           -1000.000             735.000             207.000             732.300              6
       22             207.000             732.300             245.000             726.500              6
 TYPE       SOIL           EFFECTIVE          EFFECTIVE           TOTAL         PORE PRESSURE
         DESCRIPTION        COHESION        FRICTION ANGLE     UNIT WEIGHT      PARAMETER--RU
   1   ATMOSPHERE             0.0                0.0               0.0              0.0
   2   WATER                  0.0                0.0              62.400            0.0
   3   CLAY                   0.0               11.000           109.000            0.0
   4   SLIP SURFACE           0.0                0.0               0.0              0.0
   5   THRUST LINE            0.0                0.0               0.0              0.0
   6   PHREATIC SURFACE       0.0                0.0               0.0              0.0
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 SUMMARY OF INTER-SLICE FORCES ON DOWNWARD SIDE OF DESIGNATED SLICES   ---   ITERATION NO.  1

SLICE NUMBER      HOR. COMPONENT      VERT. COMPONENT     REQD. FRICTION ANGLE     HOR. POS. OF I-S FORCE
      1               1184.08               0.0                  0.0                     13.92
      2               4736.41               0.0                  0.0                     18.84
      3              10480.48               0.0                  0.0                     23.76
      4              18215.15               0.0                  0.0                     28.68
      5              28257.03               0.0                  0.0                     33.60
      6              41083.21               0.0                  0.0                     38.52
      7              56921.76               0.0                  0.0                     43.44
      8              75772.50               0.0                  0.0                     48.36
      9              73495.81               0.0                  0.0                     53.28
     10              71289.19               0.0                  0.0                     58.20
     11              69152.56               0.0                  0.0                     63.12
     12              67056.94               0.0                  0.0                     68.04
     13              64991.42               0.0                  0.0                     72.96
     14              62955.97               0.0                  0.0                     77.88
     15              60950.59               0.0                  0.0                     82.80
     16              58974.39               0.0                  0.0                     87.72
     17              57026.36               0.0                  0.0                     92.64
     18              55106.48               0.0                  0.0                     97.56
     19              53214.77               0.0                  0.0                    102.48
     20              51351.21               0.0                  0.0                    107.40
     21              49524.14               0.0                  0.0                    112.32
     22              47739.50               0.0                  0.0                    117.24
     23              45997.33               0.0                  0.0                    122.16
     24              44297.59               0.0                  0.0                    127.08
     25              42640.30               0.0                  0.0                    132.00
     26              41025.45               0.0                  0.0                    136.92
     27              39448.91               0.0                  0.0                    141.84
     28              37900.16               0.0                  0.0                    146.76
     29              36379.19               0.0                  0.0                    151.68
     30              34886.01               0.0                  0.0                    156.60
     31              33420.59               0.0                  0.0                    161.52
     32              31982.95               0.0                  0.0                    166.44
     33              30573.10               0.0                  0.0                    171.36
     34              29191.01               0.0                  0.0                    176.28
     35              27836.70               0.0                  0.0                    181.20
     36              26510.18               0.0                  0.0                    186.12
     37              25211.45               0.0                  0.0                    191.04
     38              23940.46               0.0                  0.0                    195.96
     39              22711.44               0.0                  0.0                    200.88
     40              21676.05               0.0                  0.0                    205.80
     41              20792.39               0.0                  0.0                    210.72
     42              19938.75               0.0                  0.0                    215.64
     43              19115.11               0.0                  0.0                    220.56
     44              18321.49               0.0                  0.0                    225.48
     45              17557.89               0.0                  0.0                    230.40
     46              16824.31               0.0                  0.0                    235.32
     47               8826.52               0.0                  0.0                    240.24
     48               3341.70               0.0                  0.0                    245.16
     49                513.38               0.0                  0.0                    250.08
     50                 -0.73               0.0                  0.0                    255.00

 FACTOR OF SAFETY =   1.115
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 SUMMARY OF INTER-SLICE FORCES ON DOWNWARD SIDE OF DESIGNATED SLICES  ---  ITERATION NO.  2

SLICE NUMBER      HOR. COMPONENT     VERT. COMPONENT     REQD. FRICTION ANGLE     HOR. POS. OF I-S FORCE
      1               1176.95              0.0                  0.0                    13.92
      2               4707.92              0.0                  0.0                    18.84
      3              10417.44              0.0                  0.0                    23.76
      4              18105.57              0.0                  0.0                    28.68
      5              28093.66              0.0                  0.0                    33.60
      6              40862.48              0.0                  0.0                    38.52
      7              56638.71              0.0                  0.0                    43.44
      8              75422.19              0.0                  0.0                    48.36
      9              73156.75              0.0                  0.0                    53.28
     10              70961.00              0.0                  0.0                    58.20
     11              68834.94              0.0                  0.0                    63.12
     12              66749.69              0.0                  0.0                    68.04
     13              64694.37              0.0                  0.0                    72.96
     14              62668.98              0.0                  0.0                    77.88
     15              60673.51              0.0                  0.0                    82.80
     16              58707.07              0.0                  0.0                    87.72
     17              56768.67              0.0                  0.0                    92.64
     18              54858.27              0.0                  0.0                    97.56
     19              52975.91              0.0                  0.0                   102.48
     20              51121.57              0.0                  0.0                   107.40
     21              49303.52              0.0                  0.0                   112.32
     22              47527.70              0.0                  0.0                   117.24
     23              45794.14              0.0                  0.0                   122.16
     24              44102.80              0.0                  0.0                   127.08
     25              42453.70              0.0                  0.0                   132.00
     26              40846.83              0.0                  0.0                   136.92
     27              39278.08              0.0                  0.0                   141.84
     28              37736.98              0.0                  0.0                   146.76
     29              36223.52              0.0                  0.0                   151.68
     30              34737.72              0.0                  0.0                   156.60
     31              33279.54              0.0                  0.0                   161.52
     32              31849.00              0.0                  0.0                   166.44
     33              30446.12              0.0                  0.0                   171.36
     34              29070.86              0.0                  0.0                   176.28
     35              27723.24              0.0                  0.0                   181.20
     36              26403.28              0.0                  0.0                   186.12
     37              25110.96              0.0                  0.0                   191.04
     38              23846.25              0.0                  0.0                   195.96
     39              22623.30              0.0                  0.0                   200.88
     40              21593.03              0.0                  0.0                   205.80
     41              20713.73              0.0                  0.0                   210.72
     42              19864.30              0.0                  0.0                   215.64
     43              19044.74              0.0                  0.0                   220.56
     44              18255.04              0.0                  0.0                   225.48
     45              17495.21              0.0                  0.0                   230.40
     46              16765.26              0.0                  0.0                   235.32
     47               8797.05              0.0                  0.0                   240.24
     48               3332.51              0.0                  0.0                   245.16
     49                513.42              0.0                  0.0                   250.08
     50                 -0.68              0.0                  0.0                   255.00

  FACTOR OF SAFETY =    1.120

FINAL FACTOR OF SAFETY =    1.121
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                              SLOPE STABILITY ANALYSIS
                                      BY THE
                             METHOD OF SLICES TECHNIQUE
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      JOB DESCRIPTION    --   JANBU METHOD -FINAL SLIP SURFACE ANALYSIS         --
                              ----------------------------------------------

                                         INPUT DATA
                                         ----------

      NUMBER OF STRAIGHT LINES ARE  32
      NUMBER OF MATERIAL TYPES ARE  7
      NUMBER OF LINES REQUIRED TO DESCRIBE PHREATIC SURFACES ARE  2
      NUMBER OF PHREATIC SURFACES ARE  1
      NUMBER OF SLICES = 50.0

      COORDINATES OF GIVEN STRAIGHT LINES ARE AS FOLLOWS

       NUMBER       X-1 COORDINATE      Y-1 COORDINATE      X-2 COORDINATE      Y-2 COORDINATE       TYPE
          1              0.0               759.800              8.000              757.700             1
          2              8.000             757.700              9.000              756.400             1
          3              9.000             756.400             19.000              754.800             1
          4             19.000             754.800             34.000              749.900             1
          5             34.000             749.900             62.000              745.600             1
          6             62.000             745.600             83.000              744.200             1
          7             83.000             744.200            107.000              742.700             1
          8            107.000             742.700            138.000              739.800             1
          9            138.000             739.800            198.000              736.100             1
         10            198.000             736.100            207.000              732.300             1
         11            207.000             732.300            245.000              726.500             1
         12            245.000             726.500           1000.000              726.500             1
         13          -1000.000             759.800              0.0                759.800             1
         14            245.000             726.500            252.000              723.000             2
         15            252.000             723.000            500.000              716.000             2
         16          -1000.000             700.000           1000.000              700.000             4
         17              9.000             756.400             27.500              730.000             5
         18             27.500             730.000             40.000              720.000             5
         19             40.000             720.000             52.500              715.000             5
         20             52.000             715.000             67.500              712.500             5
         21             67.500             712.500            100.000              710.000             5
         22            100.000             710.000            222.500              710.000             5
         23            222.500             710.000            237.500              715.000             5
         24            237.500             715.000            255.000              726.500             5
         25             17.500             744.000             37.500              735.000             6
         26             37.500             735.000             55.000              730.000             6
         27             55.000             730.000             90.000              725.000             6
         28             90.000             725.000            150.000              720.000             6
         29            150.000             720.000            222.500              717.500             6
         30            222.500             717.500            251.000              723.000             6
         31          -1000.000             735.000            207.000              732.300             7
         32            207.000             732.300            245.000              726.500             7

 TYPE      SOIL            EFFECTIVE          EFFECTIVE           TOTAL        PORE PRESSURE
        DESCRIPTION        COHESION        FRICTION ANGLE      UNIT WEIGHT    PARAMETER--RU
   1   ATMOSPHERE            0.0                0.0               0.0              0.0
   2   WATER                 0.0                0.0              62.400            0.0
   3   CLAY (PEAK)           2.000             16.000           109.000            0.0
   4   CLAY (RESIDUAL)       0.0               11.000           109.000            0.0
   5   SLIP SURFACE          0.0                0.0               0.0              0.0
   6   THRUST LINE           0.0                0.0               0.0              0.0
   7   PHREATIC SURFACE      0.0                0.0               0.0              0.0
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 SUMMARY OF INTER-SLICE FORCES ON DOWNWARD SIDE OF DESIGNATED SLICES   ---   ITERATION NO.  1

SLICE NUMBER      HOR. COMPONENT      VERT. COMPONENT     REQD. FRICTION ANGLE     HOR. POS. OF I-S FORCE
     1                1728.42               0.0                  0.0                    13.92
     2                6913.54            3111.09                 3.46                   18.84
     3               15342.93            6904.32                 9.35                   23.76
     4               26880.16           12096.07                12.91                   28.68
     5               34483.45           15517.55                14.13                   33.60
     6               43183.71           12338.20                 6.25                   38.52
     7               47376.95           13536.27                 6.17                   43.44
     8               51821.48           14806.14                 6.65                   48.36
     9               56517.31           16147.80                 7.09                   53.28
    10               57383.46            8197.63                 0.0                    58.20
    11               58289.05            8327.00                 0.0                    63.12
    12               59233.58            8461.94                 0.0                    68.04
    13               58729.06            8389.86                 0.0                    72.96
    14               58240.68            8320.09                 0.0                    77.88
    15               57768.42            8252.63                 0.0                    82.80
    16               57311.84            8187.40                 0.0                    87.72
    17               56870.45            4739.20                 0.0                    92.64
    18               56444.23            4703.68                 0.0                    97.56
    19               54650.28            4554.19                 0.0                   102.48
    20               52883.02            4406.91                 0.0                   107.40
    21               51150.37            4262.53                 0.0                   112.32
    22               49457.96            4121.49                 0.0                   117.24
    23               47805.81            3983.82                 0.0                   122.16
    24               46193.91            3849.49                 0.0                   127.08
    25               44622.26            3718.52                 0.0                   132.00
    26               43090.87            3590.90                 0.0                   136.92
    27               41595.80            3466.32                 0.0                   141.84
    28               40127.08            3343.92                 0.0                   146.76
    29               38684.71            1333.96                 0.0                   151.68
    30               37268.70            1285.13                 0.0                   156.60
    31               35879.00            1237.21                 0.0                   161.52
    32               34515.66            1190.20                 0.0                   166.44
    33               33178.66            1144.09                 0.0                   171.36
    34               31868.00            1098.90                 0.0                   176.28
    35               30583.68            1054.61                 0.0                   181.20
    36               29325.71            1011.23                 0.0                   186.12
    37               28094.09             968.76                 0.0                   191.04
    38               26888.79             927.20                 0.0                   195.96
    39               25723.27             887.01                 0.0                   200.88
    40               24741.39             853.15                 0.0                   205.80
    41               23903.39             824.25                 0.0                   210.72
    42               23093.86             796.34                 0.0                   215.64
    43               22312.79             769.41                 0.0                   220.56
    44               17908.18           -3455.96                 0.0                   225.48
    45               14038.63           -2709.21                 0.0                   230.40
    46               10704.21           -2065.72                 0.0                   235.32
    47                5555.18           -1072.05                 0.0                   240.24
    48                2058.11            -397.18                 0.0                   245.16
    49                 325.99             -62.91                 0.0                   250.08
    50                  -0.23               0.0                  0.0                   255.00

  FACTOR OF SAFETY =   1.176
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 SUMMARY OF INTER-SLICE FORCES ON DOWNWARD SIDE OF DESIGNATED SLICES   ---   ITERATION NO.  2

SLICE NUMBER      HOR. COMPONENT     VERT. COMPONENT     REQD. FRICTION ANGLE     HOR. POS. OF I-S FORCE
      1               1839.75              0.0                 0.0                    13.92
      2               3934.72           1770.62                0.0                    18.84
      3               8732.16           3929.47                0.0                    23.76
      4              15273.61           6873.12                3.51                   28.68
      5              21263.14           9568.41                7.31                   33.60
      6              32370.02           9248.57                2.89                   38.52
      7              36646.59          10470.45                3.21                   43.44
      8              41157.77          11759.36                4.16                   48.36
      9              45903.54          13115.29                4.98                   53.28
     10              47365.72           6766.53                0.0                    58.20
     11              48629.96           6947.14                0.0                    63.12
     12              49931.30           7133.04                0.0                    68.04
     13              49784.10           7112.01                0.0                    72.96
     14              49650.43           7092.92                0.0                    77.88
     15              49530.28           7075.75                0.0                    82.80
     16              49423.36           7060.48                0.0                    87.72
     17              49143.04           4095.25                0.0                    92.64
     18              49063.34           4088.61                0.0                    97.56
     19              47601.91           3966.82                0.0                   102.48
     20              46162.21           3846.85                0.0                   107.40
     21              44750.71           3729.22                0.0                   112.32
     22              43371.98           3614.33                0.0                   117.24
     23              42026.07           3502.17                0.0                   122.16
     24              40712.93           3392.74                0.0                   127.08
     25              39432.59           3286.05                0.0                   132.00
     26              38185.04           3182.09                0.0                   136.92
     27              36967.08           3080.59                0.0                   141.84
     28              35770.59           2980.88                0.0                   146.76
     29              34344.50           1184.29                0.0                   151.68
     30              33200.13           1144.83                0.0                   156.60
     31              32077.04           1106.10                0.0                   161.52
     32              30975.23           1068.11                0.0                   166.44
     33              29894.73           1030.85                0.0                   171.36
     34              28835.50            994.33                0.0                   176.28
     35              27797.57            958.54                0.0                   181.20
     36              26780.93            923.48                0.0                   186.12
     37              25785.59            889.16                0.0                   191.04
     38              24811.51            855.57                0.0                   195.96
     39              23869.59            823.09                0.0                   200.88
     40              23076.07            795.73                0.0                   205.80
     41              22398.84            772.37                0.0                   210.72
     42              21744.61            749.81                0.0                   215.64
     43              21113.38            728.05                0.0                   220.56
     44              14821.59          -2860.31                0.0                   225.48
     45              11476.99          -2214.86                0.0                   230.40
     46               8594.91          -1656.67                0.0                   235.32
     47               4476.01           -863.79                0.0                   240.24
     48               1676.57           -323.93                0.0                   245.16
     49                284.50            -54.90                0.0                   250.08
     50                 -0.38              0.0                 0.0                   255.00

 FACTOR OF SAFETY =    1.463
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SUMMARY OF INTER-SLICE FORCES ON DOWNWARD SIDE OF DESIGNATED SLICES   ---   ITERATION NO.  3

SLICE NUMBER     HOR. COMPONENT     VERT. COMPONENT     REQD. FRICTION ANGLE     HOR. POS. OF I-S FORCE
      1              1781.12              0.0                 0.0                      13.92
      2              5237.64           2356.94                0.0                      18.84
      3             11623.69           5230.66                4.20                     23.76
      4             20364.36           9163.96                9.00                     28.68
      5             26649.48          11992.26               10.94                     33.60
      6             35816.48          10233.28                4.19                     38.52
      7             39967.64          11419.32                4.30                     43.44
      8             44354.82          12672.80                5.04                     48.36
      9             48978.02          13993.72                5.69                     53.28
     10             50223.89           7174.84                0.0                      58.20
     11             51380.04           7340.00                0.0                      63.12
     12             52573.82           7510.54                0.0                      68.04
     13             52326.74           7475.25                0.0                      72.96
     14             52093.95           7441.99                0.0                      77.88
     15             51875.45           7410.78                0.0                      82.80
     16             51670.91           7381.55                0.0                      87.72
     17             51290.78           4274.23                0.0                      92.64
     18             51113.74           4259.48                0.0                      97.56
     19             49559.85           4129.98                0.0                     102.48
     20             48029.09           4002.42                0.0                     107.40
     21             46528.29           3877.36                0.0                     112.32
     22             45062.36           3755.20                0.0                     117.24
     23             43631.30           3635.94                0.0                     122.16
     24             42235.11           3519.59                0.0                     127.08
     25             40873.77           3406.15                0.0                     132.00
     26             39547.31           3295.61                0.0                     136.92
     27             38252.31           3187.69                0.0                     141.84
     28             36980.13           3081.68                0.0                     146.76
     29             35490.21           1223.80                0.0                     151.68
     30             34271.71           1181.78                0.0                     156.60
     31             33075.86           1140.55                0.0                     161.52
     32             31902.68           1100.09                0.0                     166.44
     33             30752.18           1060.42                0.0                     171.36
     34             29624.33           1021.53                0.0                     176.28
     35             28519.16            983.42                0.0                     181.20
     36             27436.66            946.09                0.0                     186.12
     37             26376.83            909.55                0.0                     191.04
     38             25339.64            873.78                0.0                     195.96
     39             24336.70            839.20                0.0                     200.88
     40             23491.78            810.06                0.0                     205.80
     41             22770.67            785.20                0.0                     210.72
     42             22074.06            761.17                0.0                     215.64
     43             21401.93            738.00                0.0                     220.56
     44             15353.83          -2963.02                0.0                     225.48
     45             11931.71          -2302.61                0.0                     230.40
     46              6982.83          -1733.53                0.0                     235.32
     47              4672.89           -901.79                0.0                     240.24
     48              1745.71           -336.89                0.0                     245.16
     49               290.10            -55.98                0.0                     250.08
     50                -0.04              0.0                 0.0                     255.00

 FACTOR OF SAFETY =   1.373
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  SUMMARY OF  INTER-SLICE FORCES ON DOWNWARD SIDE OF DESIGNATED SLICES    ---   ITERATION NO.  4

SLICE NUMBER      HOR. COMPONENT      VERT. COMPONENT      REQD. FRICTION ANGLE      HOR. POS. OF I-S FORCE
      1                1801.82              0.0               0.0                      13.92
      2                4666.51            2099.93             0.0                      18.84
      3               10356.21            4660.29             1.56                     23.76
      4               18127.23            8157.25             6.98                     28.68
      5               24385.85           10973.63             9.62                     33.60
      6               34484.67            9852.76             3.72                     38.52
      7               38689.25           11054.07             3.90                     43.44
      8               43129.68           12322.76             4.72                     48.36
      9               47805.95           13658.84             5.43                     53.28
     10               49127.66            7018.23             0.0                      58.20
     11               50324.89            7189.27             0.0                      63.12
     12               51559.55            7365.65             0.0                      68.04
     13               51351.23            7335.89             0.0                      72.96
     14               51156.90            7308.13             0.0                      77.88
     15               50976.57            7282.36             0.0                      82.80
     16               50809.92            7258.56             0.0                      87.72
     17               50469.95            4205.82             0.0                      92.64
     18               50330.59            4194.21             0.0                      97.56
     19               48813.11            4067.76             0.0                     102.48
     20               47318.21            3943.18             0.0                     107.40
     21               45852.57            3821.05             0.0                     112.32
     22               44420.98            3701.75             0.0                     117.24
     23               43023.45            3585.29             0.0                     122.16
     24               41659.96            3471.66             0.0                     127.08
     25               40330.52            3360.88             0.0                     132.00
     26               39035.13            3252.93             0.0                     136.92
     27               37770.47            3147.54             0.0                     141.84
     28               36528.10            3044.01             0.0                     146.76
     29               35065.64            1209.16             0.0                     151.68
     30               33876.16            1168.14             0.0                     156.60
     31               32708.80            1127.89             0.0                     161.52
     32               31563.57            1088.40             0.0                     166.44
     33               30440.48            1049.67             0.0                     171.36
     34               29339.50            1011.71             0.0                     176.28
     35               28260.65             974.51             0.0                     181.20
     36               27203.94             938.07             0.0                     186.12
     37               26169.36             902.39             0.0                     191.04
     38               25156.89             867.48             0.0                     195.96
     39               24177.84             833.72             0.0                     200.88
     40               23353.05             805.28             0.0                     205.80
     41               22649.12             781.00             0.0                     210.72
     42               21969.11             757.56             0.0                     215.64
     43               21312.99             734.93             0.0                     220.56
     44               15237.35           -2940.54             0.0                     225.48
     45               11834.16           -2283.78             0.0                     230.40
     46                8901.60           -1717.85             0.0                     235.32
     47                4632.11            -893.91             0.0                     240.24
     48                1732.39            -334.32             0.0                     245.16
     49                 289.33             -55.84             0.0                     250.08
     50                  -0.09              0.0               0.0                     255.00

   FACTOR OF SAFETY =    1.406
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 SUMMARY OF INTER-SLICE FORCES ON DOWNWARD SIDE OF DESIGNATED SLICES   ---   ITERATION NO.  5

SLICE NUMBER      HOR. COMPONENT      VERT. COMPONENT      REQD. FRICTION ANGLE      HOR. POS. OF I-S FORCE
       1                 1793.23              0.0                  0.0                       13.92
       2                 4919.98           2213.99                 0.0                       18.84
       3                10918.72           4913.42                 2.81                      23.76
       4                19122.63           8605.18                 7.94                      28.68
       5                25366.51          11414.93                10.23                      33.60
       6                35051.78          10014.79                 3.92                      38.52
       7                39233.67          11209.62                 4.07                      43.44
       8                43651.45          12471.84                 4.85                      48.36
       9                48305.11          13801.46                 5.54                      53.28
      10                49594.51           7084.93                 0.0                       58.20
      11                50774.20           7253.45                 0.0                       63.12
      12                51991.42           7427.34                 0.0                       68.04
      13                51766.45           7395.20                 0.0                       72.96
      14                51555.61           7365.09                 0.0                       77.88
      15                51358.89           7336.98                 0.0                       82.80
      16                51175.97           7310.85                 0.0                       87.72
      17                50818.30           4234.86                 0.0                       92.64
      18                50662.78           4221.89                 0.0                       97.56
      19                49129.62           4094.13                 0.0                      102.48
      20                47619.28           3968.27                 0.0                      107.40
      21                46138.51           3844.87                 0.0                      112.32
      22                44692.13           3724.34                 0.0                      117.24
      23                43280.16           3606.68                 0.0                      122.16
      24                41902.59           3491.88                 0.0                      127.08
      25                40559.42           3379.95                 0.0                      132.00
      26                39250.65           3270.89                 0.0                      136.92
      27                37972.93           3164.41                 0.0                      141.84
      28                36717.73           3059.81                 0.0                      146.76
      29                35242.97           1215.27                 0.0                      151.68
      30                34041.01           1173.83                 0.0                      156.60
      31                32861.40           1133.15                 0.0                      161.52
      32                31704.16           1093.25                 0.0                      166.44
      33                30569.29           1054.11                 0.0                      171.36
      34                29456.76           1015.75                 0.0                      176.28
      35                28366.59            978.16                 0.0                      181.20
      36                27298.80            941.34                 0.0                      186.12
      37                26253.36            905.29                 0.0                      191.04
      38                25230.27            870.01                 0.0                      195.96
      39                24240.95            835.89                 0.0                      200.88
      40                23407.50            807.16                 0.0                      205.80
      41                22696.19            782.63                 0.0                      210.72
      42                22009.04            758.93                 0.0                      215.64
      43                21346.05            736.07                 0.0                      220.56
      44                15270.63          -2946.96                 0.0                      225.48
      45                11860.63          -2288.89                 0.0                      230.40
      46                 8922.19          -1721.83                 0.0                      235.32
      47                 4642.29           -695.88                 0.0                      240.24
      48                 1735.50           -334.92                 0.0                      245.16
      49                  289.37            -55.84                 0.0                      250.08
      50                   -0.15              0.0                  0.0                      255.00

  FACTOR OF SAFETY =   1.392
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SUMMARY OF INTER-SLICE FORCES ON DOWNWARD SIDE OF DESIGNATED SLICES   ---   ITERATION NO.  6

SLICE NUMBER     HOR. COMPONENT     VERT. COMPONENT     REQD. FRICTION ANGLE     HOR. POS. OF I-S FORCE
      1              1796.99              0.0                 0.0                     13.92
      2              4807.68           2163.45                0.0                     18.84
      3             10669.48           4801.27                2.27                    23.76
      4             18680.37           8406.16                7.53                    28.68
      5             24937.77          11222.00                9.97                    33.60
      6             34803.63           9943.89                3.83                    38.52
      7             38995.41          11141.54                4.00                    43.44
      8             43423.07          12406.59                4.79                    48.36
      9             48086.60          13739.02                5.49                    53.28
     10             49390.07           7055.72                0.0                     58.20
     11             50577.46           7225.35                0.0                     63.12
     12             51802.34           7400.33                0.0                     68.04
     13             51584.68           7369.24                0.0                     72.96
     14             51381.10           7340.16                0.0                     77.88
     15             51191.58           7313.08                0.0                     82.80
     16             51015.81           7287.97                0.0                     87.72
     17             50665.94           4222.16                0.0                     92.64
     18             50517.52           4209.79                0.0                     97.56
     19             48991.26           4082.60                0.0                    102.48
     20             47487.71           3957.31                0.0                    107.40
     21             46013.59           3834.46                0.0                    112.32
     22             44573.71           3714.48                0.0                    117.24
     23             43168.10           3597.34                0.0                    122.16
     24             41796.72           3483.06                0.0                    127.08
     25             40459.59           3371.63                0.0                    132.00
     26             39156.70           3263.06                0.0                    136.92
     27             37884.72           3157.06                0.0                    141.84
     28             36635.16           3052.93                0.0                    146.76
     29             35165.86           1212.62                0.0                    151.68
     30             33969.39           1171.36                0.0                    156.60
     31             32795.16           1130.87                0.0                    161.52
     32             31643.20           1091.14                0.0                    166.44
     33             30513.51           1052.19                0.0                    171.36
     34             29406.06           1014.00                0.0                    176.28
     35             28320.87            976.58                0.0                    181.20
     36             27257.95            939.93                0.0                    186.12
     37             26217.29            904.04                0.0                    191.04
     38             25198.86            868.93                0.0                    195.96
     39             24214.05            834.97                0.0                    200.88
     40             23384.41            806.36                0.0                    205.80
     41             22676.35            781.94                0.0                    210.72
     42             21992.33            758.36                0.0                    215.64
     43             21332.36            735.60                0.0                    220.56
     44             15258.67          -2944.65                0.0                    225.48
     45             11851.52          -2287.14                0.0                    230.40
     46              8915.55          -1720.55                0.0                    235.32
     47              4638.99           -895.24                0.0                    240.24
     48              1734.47           -334.72                0.0                    245.16
     49               289.29            -55.83                0.0                    250.08
     50                -0.23              0.0                 0.0                    255.00

  FACTOR OF SAFETY =    1.398
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 SUMMARY OF INTER-SLICE FORCES ON DOWNWARD SIDE OF DESIGNATED SLICES   ---   ITERATION NO. 7
SLICE NUMBER     HOR. COMPONENT     VERT. COMPONENT     REQD. FRICTION ANGLE     HOR. POS. OF I-S FORCE
      1              1795.33              0.0                  0.0                     13.92
      2              4857.51           2185.88                 0.0                     18.84
      3             10780.08           4851.03                 2.51                    23.76
      4             18877.20           8494.74                 7.72                    28.68
      5             25126.74          11307.03                10.08                    33.60
      6             34913.52           9975.29                 3.87                    38.52
      7             39100.93          11171.69                 4.03                    43.44
      8             43524.21          12435.48                 4.82                    48.36
      9             48183.38          13766.68                 5.52                    53.28
     10             49480.61           7068.66                 0.0                     58.20
     11             50664.58           7237.80                 0.0                     63.12
     12             51886.06           7412.29                 0.0                     68.04
     13             51665.16           7380.73                 0.0                     72.96
     14             51458.35           7351.19                 0.0                     77.88
     15             51265.64           7323.66                 0.0                     82.80
     16             51086.70           7298.10                 0.0                     87.72
     17             50733.35           4227.78                 0.0                     92.64
     18             50581.78           4215.14                 0.0                     97.56
     19             49052.45           4087.70                 0.0                    102.48
     20             47545.89           3962.16                 0.0                    107.40
     21             46068.82           3839.07                 0.0                    112.32
     22             44626.05           3718.84                 0.0                    117.24
     23             43217.62           3601.47                 0.0                    122.16
     24             41843.50           3486.96                 0.0                    127.08
     25             40503.68           3375.31                 0.0                    132.00
     26             39198.18           3266.51                 0.0                    136.92
     27             37923.65           3160.30                 0.0                    141.84
     28             36671.58           3055.96                 0.0                    146.76
     29             35199.85           1213.79                 0.0                    151.68
     30             34000.95           1172.45                 0.0                    156.60
     31             32824.33           1131.87                 0.0                    161.52
     32             31670.03           1092.07                 0.0                    166.44
     33             30538.03           1053.04                 0.0                    171.36
     34             29428.32           1014.77                 0.0                    176.28
     35             28340.93            977.27                 0.0                    181.20
     36             27275.84            940.55                 0.0                    186.12
     37             26233.07            904.59                 0.0                    191.04
     38             25212.57            869.40                 0.0                    195.96
     39             24225.76            835.37                 0.0                    200.88
     40             23394.43            806.70                 0.0                    205.80
     41             22684.92            782.24                 0.0                    210.72
     42             21999.51            758.60                 0.0                    215.64
     43             21338.20            735.80                 0.0                    220.56
     44             15263.45          -2945.58                 0.0                    225.48
     45             11855.05          -2287.82                 0.0                    230.40
     46              8918.00          -1721.02                 0.0                    235.32
     47              4640.17           -695.47                 0.0                    240.24
     48              1734.79           -334.78                 0.0                    245.16
     49               289.26            -55.82                 0.0                    250.08
     50                -0.27              0.0                  0.0                    255.00

 FACTOR OF SAFETY =   1.395
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  SUMMARY OF INTER-SLICE FORCES ON DOWNWARD SIDE OF DESIGNATED SLICES   ---   ITERATION NO.  8

 SLICE NUMBER     HOR. COMPONENT     VERT. COMPONENT     REQD. FRICTION ANGLE     HOR. POS. OF I-S FORCE
       1             1796.07              0.0                  0.0                    13.92
       2             4835.42           2175.94                 0.0                    18.84
       3            10731.05           4828.97                 2.41                   23.76
       4            18789.66           8455.34                 7.63                   28.68
       5            25043.19          11269.43                10.03                   33.60
       6            34864.75           9961.35                 3.85                   38.52
       7            39054.11          11158.31                 4.02                   43.44
       8            43479.34          12422.66                 4.81                   48.36
       9            48140.45          13754.41                 5.51                   53.28
      10            49440.45           7062.92                 0.0                    58.20
      11            50625.95           7232.28                 0.0                    63.12
      12            51848.94           7406.99                 0.0                    68.04
      13            51629.49           7375.64                 0.0                    72.96
      14            51424.12           7346.30                 0.0                    77.88
      15            51232.83           7316.97                 0.0                    82.80
      16            51055.30           7293.61                 0.0                    87.72
      17            50703.50           4225.29                 0.0                    92.64
      18            50553.34           4212.77                 0.0                    97.56
      19            49025.38           4085.45                 0.0                   102.48
      20            47520.16           3960.01                 0.0                   107.40
      21            46044.41           3637.03                 0.0                   112.32
      22            44602.93           3716.91                 0.0                   117.24
      23            43195.75           3599.64                 0.0                   122.16
      24            41822.85           3485.24                 0.0                   127.08
      25            40484.23           3373.69                 0.0                   132.00
      26            39179.90           3264.99                 0.0                   136.92
      27            37906.51           3158.87                 0.0                   141.84
      28            36655.56           3054.63                 0.0                   146.76
      29            35184.91           1213.27                 0.0                   151.68
      30            33987.09           1171.97                 0.0                   156.60
      31            32811.54           1131.43                 0.0                   161.52
      32            31658.29           1091.66                 0.0                   166.44
      33            30527.32           1052.67                 0.0                   171.36
      34            29418.62           1014.44                 0.0                   176.28
      35            28332.21            976.97                 0.0                   181.20
      36            27268.09            940.28                 0.0                   186.12
      37            26226.25            904.35                 0.0                   191.04
      38            25206.68            869.20                 0.0                   195.96
      39            24220.76            835.20                 0.0                   200.88
      40            23390.18            806.56                 0.0                   205.80
      41            22681.32            782.11                 0.0                   210.72
      42            21996.53            758.50                 0.0                   215.64
      43            21335.82            735.72                 0.0                   220.56
      44            15261.60          -2945.22                 0.0                   225.48
      45            11853.76          -2287.57                 0.0                   230.40
      46             8917.19          -1720.86                 0.0                   235.32
      47             4639.88           -695.42                 0.0                   240.24
      48             1734.86           -334.80                 0.0                   245.16
      49              289.47            -55.86                 0.0                   250.08
      50               -0.06              0.0                  0.0                   255.00

   FACTOR OF SAFETY =   1.397

FINAL FACTOR OF SAFETY =   1.396
```

SOURCE LISTINGS

"SLOPO"

SLOPE STABILITY PROGRAM

MAINPGM

```
C
C..............................................................................
C
C        SLOPO       MAIN PROGRAM        SLOPE STABILITY ANALYSIS
C
C                       PROGRAMMED AND DOCUMENTED
C                                  BY
C                     R.A. VAN CAUWENBERGHE, P.ENG.
C                                 1970
C
C                        IN PARTIAL FULFILLMENT
C                  OF THE REQUIREMENTS FOR THE DEGREE
C                           MASTER OF SCIENCE
C               FACULTY OF GRADUATE STUDIES AND RESEARCH
C                        UNIVERSITY OF MANITOBA
C
C..............................................................................
C
C        PURPOSE
C            TO CALCULATE THE FACTOR OF SAFETY IN THE SLOPE
C            STABILITY ANALYSIS BY THE METHOD OF SLICES PROCEDURE
C            FOR AN EARTH OR ROCK SLOPE OR EMBANKMENT
C
C        OPTIONS
C            SLOPO WILL ANALYSE THE STABILITY OF A SLOPE BY ONE
C            OF THE FOLLOWING METHODS
C            1. BISHOP'S METHOD OF SLICES
C            2. SIMPLIFIED OR ORDINARY METHOD OF SLICES
C            3. JANBU METHOD OF SLICES
C
C
C..............................................................................
C
C
C              ******   INPUT  DATA  CARD  FORMAT   ******
C
C  *CARD*  VARIABLE  COLUMN   DESCRIPTION AND REMARKS
C    NO.               NO.
C  ......  ........  ......   .....................................
C
C    1     A           1      A=1 -REQUEST ANALYSIS BY BISHOP'S METHOD
C                                  OF SLICES.
C                             A=0 -NO REQUEST OF ANALYSIS BY BISHOP'S
C                                  METHOD OF SLICES.
C                             OPTION 1.       ASSUMPTIONS
C                                               -CIRCULAR SLIP SURFACE
C                                               -HORIZONTAL INTER-SLICE
C                                                FORCES
C          B           2      B=1 -REQUEST ANALYSIS BY SIMPLIFIED
C                                  METHOD OF SLICES
C                             B=0 -NO REQUEST OF ANALYSIS BY SIMPLIFIED
C                                  METHOD OF SLICES
C                             OPTION 2.       ASSUMPTIONS
C                                               -CIRCULAR SLIP SURFACE
```

MAINPGM

```
C  *CARD*  VARIABLE  COLUMN   DESCRIPTION AND REMARKS
C    NO.               NO.
C  ......  ........  ......   .......................................
C
C                                             -NO INTER-SLICE FORCES
C                             NOTE. OPTION 1 AND OPTION 2 CAN BE
C                                   EMPLOYED SIMULTANEOUSLY IN THE
C                                   SAME PROBLEM.
C          C           3      C=1 -REQUEST ANALYSIS BY JANBU METHOD
C                                  OF SLICES
C                             C=0 -NO REQUEST OF ANALYSIS BY JANBU
C                                  METHOD OF SLICES.
C                             OPTION 3.      ASSUMPTIONS
C                                             -NON-CIRCULAR SLIP
C                                              SURFACE. SLIP SURFACE
C                                              APPROXIMATED BY A SERIES
C                                              OF STRAIGHT LINES.
C                                             -CHOICE OF HORIZONTAL
C                                              INTER-SLICE FORCES *OR*
C                                              VERTICAL AND HORIZONTAL
C                                              INTER-SLICE FORCES.
C                             NOTE. OPTION 3 CAN NOT BE EMPLOYED IN THE
C                                   SAME PROBLEM WITH EITHER OPTION 1
C                                   OR OPTION 2.
C          JOB DES-
C          CRIPTION   4 -50   PROVISION TO INSERT EITHER OR ALL OF THE
C                             FOLLOWING INFORMATION - JOB OR PROJECT
C                             DESCRIPTION, JOB NUMBER, LOCATION, DATES,
C                             ETC.
C                             MAXIMUM NUMBER OF CHARACTERS = 47
C                             A-FORMAT
C
C     2    NO. OF
C          SLICES     1 -10   NUMBER OF SLICES REQUIRED
C
C     3    NO. OF
C          CENTERS    1 - 5   NUMBER OF SPECIFIED CIRCLE CENTERS.
C                             SET EQUAL TO ZERO FOR OPTION 3.
C          NO. OF
C          RADIUS
C          TESTS      6 -10   NUMBER OF ANALYSES TO BE CONDUCTED
C                             AT EACH CIRCLE CENTER. EACH ANALYSIS
C                             TO HAVE DIFFERENT RADIUS AS PER RADIUS
C                             DECREMENT.
C          RADIUS
C          DECREM.   11 -20   TO BE EMPLOYED IN CONJUNCTION WITH
C                             'NO. OF RADIUS TESTS'.
C                             FIRST ANALYSIS CONDUCTED AT A PARTICULAR
C                             CIRCLE CENTER WITH SPECIFIED RADIUS, AND
C                             EACH SUCCEEDING ANALYSIS AT THE SAME
C                             CIRCLE CENTER WILL HAVE A RADIUS REDUCED
C                             BY THE VALUE 'RADIUS DECREMENT'.
C          CENTER
C          INCREM.   21 -30   WHEN GREATER THAN ZERO, AN ANALYSIS IS
```

```
C   *CARD*  VARIABLE  COLUMN   DESCRIPTION AND REMARKS
C     NO.              NO.
C   ......  ........  ......   ........................................
C
C                              AUTOMATICALLY CONDUCTED FOR EACH OF THE
C                              EIGHT CIRCLE CENTERS ABOUT THE SPECIFIED
C                              CIRCLE CENTER. HORIZONTAL AND/OR VERTICAL
C                              DISTANCE OF ANY ADDITIONAL CIRCLE CENTER
C                              FROM THE SPECIFIED CIRCLE CENTER IS EQUAL
C                              TO THE VALUE 'CENTER INCREMENT'.
C
C     4     NO. OF
C           LINES     1 - 5    TOTAL NUMBER OF STRAIGHT LINES REQUIRED
C                              TO DESCRIBE SURFACE PROFILE, SOIL OR ROCK
C                              LAYERS, WATER SURFACE, PHREATIC SURFACE,
C                              AND (FOR OPTION 3 ONLY) SLIP SURFACE, AND
C                              THRUST LINE.
C                              NOTES.
C                                   1. X-1 COORDINATE MUST BE LESS THAN
C                                      X-2 COORDINATE.
C                                   2. VERTICAL LINES WILL NOT BE
C                                      ACCEPTED.  SLOPES OF ALL LINES
C                                      SHOULD BE LESS THAN 1 TO 500.
C           NO. OF
C           TYPES     6 -10    TOTAL NUMBER OF MATERIAL TYPES.
C                              THIS PARAMETER SPECIFIES THE TYPE OF
C                              MATERIAL IMMEDIATELY ABOVE A LINE.
C                              NOTES.
C                                   1. NORMALLY ATMOSPHERE WOULD BE
C                                      SPECIFIED AS MATERIAL TYPE NO. 1.
C
C                                       * OPTION 1 AND OPTION 2 *
C                                   2. THE N'TH MATERIAL TYPE LINES DEFINE
C                                      THE PHREATIC SURFACE IF A PHREATIC
C                                      SURFACE IS INSERTED.
C                                   3. IF 'RADIUS' OF A SPECIFIED CIRCLE
C                                      CENTER IS GIVEN THE VALUE ZERO,
C                                      (REFER TO RADIUS COMMENT) A RADIUS
C                                      DETERMINATION IS IMPLIED.  THE
C                                      SHORTEST DISTANCE FROM THE CIRCLE
C                                      CENTER TO THE SERIES OF LINES
C                                      DEFINED BY THE MATERIAL TYPE NUMBER
C                                      N - 1 (OR 'N' IF PHREATIC SURFACE
C                                      NOT EMPLOYED) WILL BE THE
C                                      DETERMINED RADIUS.
C
C                                               * OPTION 3 *
C                                   4. THE N'TH MATERIAL TYPE LINES DEFINE
C                                      THE PHREATIC SURFACE IF A PHREATIC
C                                      SURFACE IS INSERED.
C                                   5. THE N'TH - 1 MATERIAL TYPE LINES
C                                      DEFINE THE THRUST LINE. IF A
C                                      THRUST LINE IS NOT INSERTED A
C                                      HORZONTAL THRUST LINE WILL BE
```

MAINPGM

```
C   *CARD*  VARIABLE  COLUMN   DESCRIPTION AND REMARKS
C    NO.               NO.
C   ......  ........  ......   ..........................................
C
C                                       ASSUMED. NOTE THAT A MATERIAL TYPE
C                                       NUMBER MUST BE RESERVED FOR THE
C                                       HORIZONTAL THRUST LINE ASSUMPTION.
C                                       (THE MATERIAL TYPE NUMBER WILL BE
C                                       N IF A PHREATIC SURFACE NOT
C                                       INSERTED).
C                                    6. THE N'TH - 2 MATERIAL TYPE LINES
C                                       DEFINE THE SLIP SURFACE. (N-1 IF
C                                       PHREATIC SURFACE NOT INSERTED).
C           C         11 -15   NUMBER OF LINES TO DESCRIBE PHREATIC
C                              SURFACE.
C           D         20       D=0 -NO PHREATIC SURFACE
C                              D=1 -PHREATIC SURFACE INSERTED
C
C 5-'NO.OF
C   LINES' LINE NO.    1 - 5   LINE IDENTIFIER
C                              LINE CARDS TO BE ARRANGED IN SEQUENCE
C                              FROM UNITY TO 'NO. OF LINES'.
C                              NOTE.  ALL PHREATIC SURFACE LINE DATA
C                                     (IF ANY EXISTS) MUST BE PLACED
C                                     AT THE END OF THE LINE DATA
C                                     SEQUENCE.
C          X-1 CO-
C          ORDINATE    6 -15   POSITIVE OR NEGATIVE ABSCISSA (FEET)
C          Y-1 CO-
C          ORDINATE   16 -25   POSITIVE ORDINATE PERTAINING TO X-1 (FEET)
C          X-2 CO-
C          ORDINATE   26 -35   (FEET)
C          Y-2 CO-
C          ORDINATE   36 -45   (FEET)
C          TYPE NO.   46 -50   MATERIAL TYPE ABOVE SPECIFIED LINE
C
C MATERIAL
C DESC.
C CARDS    TYPE NO.    1 - 4   MATERIAL TYPE NUMBER
C          MATERIAL
C          DESC.       5 -22   DESCRIPTON OF MATERIAL
C          COHESION   23 -29   COHESIVE SHEAR STRENGTH PARAMETER OF
C                              MATERIAL (POUNDS PER SQUARE INCH)
C          PHI        30 -34   INTERNAL FRICTION ANGLE SHEAR STRENGTH
C                              PARAMETER OF MATERIAL (DEGREES)
C          UNIT WT.   35 -44   TOTAL UNIT WEIGHT OF MATERIAL
C                              (POUNDS PER CUBIC FOOT)
C          RU         45 -50   POREWATER PRESSURE PARAMETER
C                              (DIMENSIONLESS)
C                              DEFINED AS RATIO OF POREWATER PRESSURE
C                              TO OVERBURDEN AT POINT OF CONCERN
C
C
C
```

MAINPGM

```
C  *CARD*  VARIABLE  COLUMN   DESCRIPTION AND REMARKS
C    NO.              NO.
C  ......  ........  ......   ..........................................
C
C CIRCLE
C CENTER
C DATA      X  CO-
C           ORDINATE   1 -10   POSITIVE OR NEGATIVE (FEET)
C           Y  CO-
C           ORDINATE  11 -20   POSITIVE (FEET)
C
C           RADIUS    21 -30   (FEET)
C                              IF RADIUS IS NOT GIVEN, A RADIUS
C                              DETERMINATION IS IMPLIED.
C
C
C
C
C
C......................................................................
C
C
C
C      DESCRIPTION OF PARAMETERS       -  INPUT FUNCTIONS
C
C          A       -SPECIFIED RADIUS OF SLIP CIRCLE
C          ASLI    -NUMBER OF SLICES.
C          COHES   -COHESION SHEAR STRENGTH PARAMETER OF MATERIAL TYPE
C                   IN UNITS OF POUNDS PER SQUARE INCH
C          DESC    -DESCRIPTION OF MATERIAL TYPE
C          DESJO   -JOB OR PROJECT DESCRIPTION
C          HX      -HORIZONTAL COORDINATE OF SLIP CIRCLE CENTER
C          HY      -VERTICAL COORDINATE OF SLIP CIRCLE CENTER
C          JPROP   -NUMBER IDENTIFYING THE TYPE OF MATERIAL IMMEDIATELY
C                   ABOVE THE LINE IN QUESTION
C          KOUNT   -NUMBER OF SPECIFIED CIRCLE CENTERS.
C                   KOUNT = 0 FOR OPTION 3
C          L       -NUMBER OF MATERIAL TYPE
C          LINE    -LINE NUMBER.  ALL LINES TO BE IDENTIFIED BY A
C                   NUMBER STARTING FROM '1' TO 'LINES'.
C          LINES   -TOTAL NUMBER OF STRAIGHT LINES REQUIRED TO
C                   DESCRIBE SURFACE PROFILE, SOIL OR ROCK LAYERS,
C                   WATER SURFACE, PHREATIC SURFACE, AND (FOR
C                   OPTION 3 ONLY) SLIP SURFACE, AND THRUST LINE.
C                   NOTE. VERTICAL LINES WILL NOT BE ACCEPTED.
C                         SLOPES OF ALL LINES SHOULD BE LESS THAN
C                         500 TO 1.
C          LNS     -TOTAL NUMBER OF LINES TO DESCRIBE PHREATIC SURFACE
C          NBIS    -INPUT REQUEST 'A'. THIS REQUEST WILL ANALYSE
C                   SLOPE BY OPTION 1 (BISHOP'S METHOD OF SLICES).
C                   A = 1 -REQUEST ANALYSIS BY OPTION 1
C                   A = 0 -NO REQUEST OF OPTION 1
C                   NOTE. OPTION 1 CAN BE EMPLOYED SIMULTANEOUSLY
C                         WITH OPTION 2 BUT NOT WITH OPTION 3.
```

MAINPGM

```
C               NJAN    -INPUT REQUEST 'C'. THIS REQUEST WILL ANALYSE
C                        SLOPE BY OPTION 3 (JANBU METHOD OF SLICES).
C                        C = 1 -REQUEST ANALYSIS BY OPTION 3
C                        C = 0 -NO REQUEST OF OPTION 3
C                        NOTE. OPTION 3 CAN NOT BE EMPLOYED IN THE SAME
C                              PROBLEM WITH EITHER OPTION 1 OR OPTION 2.
C               NPHR    -'D'= 1  IF PHREATIC SURFACE INSERTED
C                        'D'= 0  IF PHREATIC SURFACE NOT INSERTED
C               NRED    -NUMBER OF RADIUS TESTS.  THIS SPECIFIES THE
C                        NUMBER OF TESTS TO BE CONDUCTED AT A SPECIFIC
C                        CIRCLE CENTER WITH RADIUS BEING THE ONLY VARIABLE
C               NSIM    -INPUT REQUEST 'B'. THIS REQUEST WILL ANALYSE
C                        SLOPE BY OPTION 2 (SIMPLIFIED METHOD OR
C                        ORDINARY METHOD OF SLICES).
C                        B = 1 -REQUEST ANALYSIS BY OPTION 2
C                        B = 0 -NO REQUEST OF OPTION 2
C                        NOTE. OPTION 2 CAN BE EMPLOYED SIMULTANEOUSLY
C                              WITH OPTION 1 BUT NOT WITH OPTION 3.
C               NTYES   -TOTAL NUMBER OF MATERIAL TYPES
C                            ATMOSPHERE AND WATER ARE TO BE CONSIDERED
C                            AS MATERIAL TYPES
C               PHI     -INTERNAL FRICTION ANGLE SHEAR STRENGTH PARAMETER
C                        OF MATERIAL TYPE IN UNITS OF DEGREES
C               RADL    -RADIUS DECREMENT WHEN NRED IS GREATER THAN ONE.
C               RU      -PORE PRESSURE PARAMETER OF MATERIAL TYPE.
C                        DIMENSIONLESS.
C                        RU IS DEFINED AS THE RATIO OF POREWATER PRESSURE
C                        TO THE OVERBURDEN AT THE POINT OR PLANE
C                        OF CONSIDERATION WHICH FOR THE PURPOSE OF THIS
C                        PROGRAM IS THE BASE OF EACH SLICE
C               STEP    -AUTOMATICALLY TESTS EIGHT CIRCLE CENTERS ABOUT
C                        THE SPECIFIED CIRCLE CENTER. HORIZONTAL AND/OR
C                        VERTICAL DISTANCE OF ANY ADDITIONAL CIRCLE
C                        CENTER FROM THE SPECIFIED CIRCLE CENTER IS
C                        EQUAL TO THE VALUE 'STEP'.
C               UNIWT   -TOTAL UNIT WEIGHT OF MATERIAL
C                        POUNDS PER CUBIC FOOT
C               X(1,I)  -THE HORIZONTAL COORDINATE OR A STRAIGHT LINE
C               X(2,I)  -THE SECOND HORIZONTAL COORDINATE OF A STRAIGHT
C                        LINE
C                        NOTE - X(1,I) MUST BE LESS THAN X(2,I)
C               Y(1,I)  -THE VERTICAL COORDINATE OF A STRAIGHT LINE
C                        CORRESPONDING TO X(1,I)
C               Y(2,I)  -THE VERTICAL COORDINATE OF A STRAIGHT LINE
C                        CORRESPONDING TO X(2,I)
C
C.....................................................................
C
C       SUBROUTINES REQUIRED
C           READR
C           STEPS
C           RADIS
C           PROFL
C           SLICE
```

MAINPGM

```
C               BISH
C               JANPA
C               JANCA
C
C
C          DIMENSIONS OF FOLLOWING VARIABLES MUST BE EQUAL TO OR
C                GREATER THAN 'NO. OF MATERIAL TYPES'.
      DIMENSION COHES(20),PHI(20),UNIWT(20),RU(20)
C
C          DIMENSIONS OF FOLLOWING VARIABLES MUST BE EQUAL TO OR
C                GREATER THAN 'NO. OF SLICES'.
      DIMENSION COBSL(100),TANPH(100),COSAP(100)
      DIMENSION BUS(100),WIGHT(100),SINAP(100)
      DIMENSION SECAP(100),TANAP(100),TANAT(100)
      DIMENSION CSAPS(100),DTO(100),DEPDN(100),XRI(100)
C
C          DIMENSIONS OF FOLLOWING VARIABLES MUST BE EQUAL TO OR
C                GREATER THAN 'NO. OF STRAIGHT LINES'.
      DIMENSION LINE(100),X(2,100),Y(2,100),JPROP(100)
      DIMENSION SLO(100),SLOPO(100),B(100)
C
C          DIMENSIONS OF FOLLOWING VARIABLES MUST BE EQUAL TO OR
C                GREATER THAN 'NO. OF SPECIFIED CIRCLE CENTERS'.
      DIMENSION HX(50),HY(50),A(50),RAD(50)
C
      COMMON NUM,NOT,NU,KT,KEP
      COMMON FS,F,JPR
      COMMON NKK,NM,KK,JJ,KEPT,KJ
      COMMON N,NNT,NN,KEEP,JM,NNN
      COMMON I,L,K,NRETA,J,NNRET
      COMMON LINES,NTYES,LNS,NPHR,LNNS,NTYPE
      COMMON IN,IO,KOUNT,NRED,NBIS,NSIM
      COMMON YHI,EXTN,SLI,BSLI,XNEXT,YTN
      COMMON EXLO,YLO,EXHI,XRET,XMID
      COMMON RADL,ASLI,RADMI
      COMMON STEP,NCEN
      COMMON NJAN
C
  202 FORMAT (4(F10.0))
  240 FORMAT (/)
C
C          IN - INPUT DEVICE CODE
C          IO - OUTPUT DEVICE CODE
C
      IN =1
      IO =3
  660 CALL READR(LINE,X,Y,JPROP,COHES,PHI,UNIWT,SLO,SLOPO,B,RU)
      IF (ASLI) 803,803,661
C
C          OPTION 3 REQUEST
C
  661 IF (NJAN) 100,100,101
C
C          COMMENCE ANALYSIS FOR EACH SPECIFIED SLIP CIRCLE CENTER
```

```
C
  100 DO 4 K=1,KOUNT
      READ(IN,202)HX(K),HY(K),A(K)
      IF (HY(K)) 636,636,804
  804 NRETA=NRED
      WRITE (IO,240)
      NCEN = 0
      RADRT = 0.
      IF (A(K)) 193,193,307
  307 RADRT = A(K)
      GO TO 305
  193 J=0
      GO TO 356
  346 CALL STEPS(HY,HX)
      NRETA = NRED
      A(K) = RADRT
      IF (A(K)) 356,356,305
  356 CALL RADIS (JPROP,SLO,HX,HY,B,X,RAD,Y,A)
      GO TO 305
  306 A(K) = A(K)-RADL
  305 CALL PROFL (SLOPO,B,SLO,HX,HY,A,X)
      IF(J-1)636,636,105
  105 CALL SLICE (X,SLO,B,HY,HX,A,JPROP,UNIWT,BUS,WIGHT,SINAP,SECAP,TANA
     1P,COBSL,TANPH,COSAP,PHI,COHES,RU)
  636 CALL BISH (WIGHT,SINAP,COBSL,TANPH,BUS,SECAP,TANAP,HX,HY,A,COSAP)
      GO TO 180
  101 CALL JANPA (JPROP,X,Y,SLO,B,UNIWT,BUS,WIGHT,TANAT,TANAP,
     C                TANPH,COHES,CSAPS,COBSL,DTO,RU,PHI,DEPDN,XRI)
      CALL JANCA (WIGHT,DTO,TANAP,BUS,TANPH,CSAPS,TANAT,COBSL,DEPDN,XRI)
      GO TO 805
  180 NRETA = NRETA -1
      IF (NRETA)655,655,306
  655 IF (STEP) 654,4,654
  654 WRITE(IO,240)
      IF (8-NCEN) 4,4,346
    4 CONTINUE
C
C         PROBLEM COMPLETED - DO NEXT ONE
C
  805 GO TO 660
  803 CONTINUE
      CALL EXIT
      END
```

READR

```
      SUBROUTINE READR (LINE,X,Y,JPROP,COHES,PHI,UNIWT,SLO,SLOPO,B,RU)
C
C.......................................................................
C
C         SUBROUTINE READR
C
C          PURPOSE
C              1. READS INPUT DATA
C              2. CALCULATES Y-INTERCEPT AND SLOPE OF
C                 EACH STRAIGHT LINE.
C
C.......................................................................
C
      DIMENSION LINE(1),X(2,1),Y(2,1),JPROP(1),COHES(1)
      DIMENSION PHI(1),UNIWT(1),SLO(1),SLOPO(1),B(1)
      DIMENSION RU(1)
      DIMENSION DESC(5)
      DIMENSION DESJO(12)
      COMMON NUM,NOT,NU,KT,KEP
      COMMON FS,F,JPR
      COMMON NKK,NM,KK,JJ,KEPT,KJ
      COMMON N,NNT,NN,KEEP,JM,NNN
      COMMON I,L,K,NRETA,J,NNRET
      COMMON LINES,NTYES,LNS,NPHR,LNNS,NTYPE
      COMMON IN,IO,KOUNT,NRED,NBIS,NSIM
      COMMON YHI,EXTN,SLI,BSLI,XNEXT,YTN
      COMMON EXLO,YLO,EXHI,XRET,XMID
      COMMON RADL,ASLI,RADMI
      COMMON STEP,NCEN
      COMMON NJAN
  200 FORMAT (I5,4(F10.0), I5)
  201 FORMAT (4(I5))
  202 FORMAT (3(F10.0))
  207 FORMAT (10X,I5,4(10X,F10.3),10X,I5)
  208 FORMAT ('1')
  209 FORMAT(1X,/,10X,'NUMBER OF STRAIGHT LINES ARE',I4,/,10X,'NUMBER OF
     1 MATERIAL TYPES ARE',I3,/,10X,'NUMBER OF LINES REQUIRED TO DESCRIB
     2E PHREATIC SURFACES ARE',I3,/,10X,'NUMBER OF PHREATIC SURFACES ARE
     3',I3)
  224 FORMAT (4X,I4,T11,4A4,A2,T28,F10.3,T49,F10.3,T68,F10.3,T90,F6.3)
  225 FORMAT (I4,4A4,A2,F7.3,F5.3,F10.3,F6.3)
  236 FORMAT (/,48X,'SLOPE STABILITY ANALYSIS',
     1         /,57X,'BY THE',
     2         /,47X,'METHOD OF SLICES TECHNIQUE',
     3         /,47X,'--------------------------',/)
  237 FORMAT (/,10X,'COORDINATES OF GIVEN STRAIGHT LINES ARE AS FOLLOWS'
     1,        //,11X,'NUMBER',8X,'X-1 COORDINATE',6X,
     2         'Y-1 COORDINATE',6X,'X-2 COORDINATE',6X,
     3         'Y-2 COORDINATE',8X,'TYPE')
  238 FORMAT(/,T5,'TYPE',T16,'SOIL',T31,'EFFECTIVE',T51,'EFFECTIVE',
     1        T72,'TOTAL',T85,'PORE PRESSURE',
     2        /,T13,'DESCRIPTION',T31,'COHESION',
     3        T49,'FRICTION ANGLE',T69,'UNIT WEIGHT',
     4        T85,'PARAMETER--RU')
```

READR

```
250 FORMAT (10X,'JOB DESCRIPTION','   --  ',1X,11A4,A3,'   --',
   1          /,33X,'--------------------------------------------------',
   2          //,55X,'INPUT DATA',/,55X,'-----------')
500 FORMAT(2(I5),2(F10.0))
501 FORMAT (3(I1),11A4,A3)
502 FORMAT (1X,'CENTER OF FAILURE ARC',T30,'RADIUS OF',T49,'GROUND SUR
   1FACE INTERSECTIONS',T83,'LOW POINT OF',T100,'FACTOR  OF  SAFETY',
   3          /,T6,'X',T15,'Y',T29,'FAILURE ARC',T54,'WITH SLIP CIRCLE',
   4          T83,'SLIP CIRCLE',T100,'SIMPLIFIED BISHOPS',/,1X,T49,'X',TS
   57,'Y',T67,'X',T75,'Y',T85,'X',T92,'Y',T100,'METHOD      METHOD')
503 FORMAT (10X,'NUMBER OF SLICES =',F5.1)
    READ(IN,501,END=102) NBIS,NSIM,NJAN,(DESJO(J),J=1,12)
    READ (IN,202)ASLI
    READ (IN,500)KOUNT,NRED,RADL,STEP
    WRITE(IO,208)
    WRITE(IO,236)
    WRITE(IO,250) (DESJO(J),J=1,12)
    READ (IN,201)LINES,NTYES,LNS,NPHR
    WRITE(IO,209)LINES,NTYES,LNS,NPHR
    WRITE (IO,503)ASLI
    WRITE(IO,237)
    LNNS = LINES - LNS
    NTYPE=NTYES - NPHR
    DO 1 I= 1,LINES
    READ (IN,200) LINE(I),X(1,I),Y(1,I),X(2,I),Y(2,I),JPROP(I)
    WRITE(IO,207) LINE(I),X(1,I),Y(1,I),X(2,I),Y(2,I),JPROP(I)
  1 CONTINUE
    WRITE(IO,238)
C
C         CALCULATE Y-INTERCEPT AND SLOPE OF EACH LINE
C
    DO 2 L=1,NTYES
    READ (IN,225) L,(DESC(KX),KX=1,5),COHES(L),PHI(L),UNIWT(L),RU(L)
    WRITE(IO,224) L,(DESC(KX),KX=1,5),COHES(L),PHI(L),UNIWT(L),RU(L)
  2 CONTINUE
    DO 5 I = 1,LINES
    IF (X(2,I)- X(1,I)) 110,120,110
110 SLO(I) = (Y(2,I) -Y(1,I)) / (X(2,I)- X(1,I))
    SLOPO(I) = ABS(SLO(I))
    B(I) = Y(1,I) - SLO(I) * X(1,I)
    GO TO 5
120 SLO(I) = 0.
    SLOPO(I) = 0.
    B(I) = 0.
  5 CONTINUE
    WRITE(IO,208)
    IF (NJAN) 100,100,101
102 ASLI = 0.
    GO TO 101
100 WRITE(IO,502)
101 RETURN
    END
```

STEPS

```
      SUBROUTINE STEPS(HY,HX)
C
C.....................................................................
C
C         SUBROUTINE STEPS
C
C          PURPOSE
C              TO AUTOMATICALLY TEST EIGHT CIRCLE CENTERS ABOUT
C              THE SPECIFIED CIRCLE CENTER.
C              HORIZONTAL AND/OR VERTICAL DISTANCE OF ANY ADDITIONAL
C              CIRCLE CENTER FROM THE SPECIFIED CIRCLE CENTER IS
C              EQUAL TO THE VALUE 'STEP'.
C
C.....................................................................
C
      DIMENSION HY(1),HX(1)
      COMMON NUM,NOT,NU,KT,KEP
      COMMON FS,F,JPR
      COMMON NKK,NM,KK,JJ,KEPT,KJ
      COMMON N,NNT,NN,KEEP,JM,NNN
      COMMON I,L,K,NRETA,J,NNRET
      COMMON LINES,NTYES,LNS,NPHR,LNNS,NTYPE
      COMMON IN,IO,KOUNT,NRED,NBIS,NSIM
      COMMON YHI,EXTN,SLI,BSLI,XNEXT,YTN
      COMMON EXLO,YLO,EXHI,XRET,XMID
      COMMON RADL,ASLI,RADMI
      COMMON STEP,NCEN
      NCEN=NCEN+1
      GO TO (340,341,342,342,343,343,340,340),NCEN
  340 HX(K)=HX(K)-STEP
      GO TO 347
  341 HY(K)=HY(K)+STEP
      GO TO 347
  342 HX(K)=HX(K)+STEP
      GO TO 347
  343 HY(K)=HY(K)-STEP
  347 RETURN
      END
```

RADIS

```
      SUBROUTINE RADIS (JPROP,SLO,HX,HY,B,X,RAD,Y,A)
C
C.......................................................................
C
C        SUBROUTINE RADIS
C
C         PURPOSE
C             TO DETERMINE THE MINIMUM RADIUS FROM A SPECIFIED
C             CIRCLE CENTER TO A PARTICULAR SURFACE
C
C.......................................................................
C
      DIMENSION JPROP(1),SLO(1),HX(1),B(1),HY(1),X(2,1),RAD(1),Y(2,1)
      DIMENSION A(1)
      COMMON NUM,NOT,NU,KT,KEP
      COMMON FS,F,JPR
      COMMON NKK,NM,KK,JJ,KEPT,KJ
      COMMON N,NNT,NN,KEEP,JM,NNN
      COMMON I,L,K,NRETA,J,NNRET
      COMMON LINES,NTYES,LNS,NPHR,LNNS,NTYPE
      COMMON IN,IO,KOUNT,NRED,NBIS,NSIM
      COMMON YHI,EXTN,SLI,BSLI,XNEXT,YTN
      COMMON EXLO,YLO,EXHI,XRET,XMID
      COMMON RADL,ASLI,RADMI
      COMMON STEP,NCEN
      NNRET=1
      N=0.
C
C        DETERMINE SHORTEST DISTANCE FROM SLIP CIRCLE CENTER
C        TO EACH STRAIGHT LINE WITH MATERIAL TYPE N-1 (OR N
C        IF PHREATIC SURFACE IS NOT PRESENT).
C
C        DETERMINE WHETHER THE SHORTEST DISTANCE IS TANGENT TO A
C        LINE OR WHETHER IT TERMINATES AT THE END POINT OF A LINE.
C
      DO 90 I=1,LNNS
      IF(JPROP(I)-NTYPE) 90,194,90
  194 N=N+1
      IF(SLO(I))195,310,195
  195 SSLO=-1./SLO(I)
      BB = HY(K) - SSLO*HX(K)
      XX = (BB - B(I))/(SLO(I) - SSLO)
      IF(XX-X(1,I))312,312,302
  312 RAD(N) = SQRT ((HX(K)-X(1,1))**2 + (HY(K)-Y(1,I))**2)
      GO TO 90
  310 IF (HX(K)-X(1,I))312,312,311
  311 IF (HX(K)-X(2,I)) 313,314,314
  313 RAD(N) = HY(K) - Y(1,I)
      GO TO 90
  302 IF (XX-X(2,I)) 303,314,314
  314 RAD(N) = SQRT((HX(K) - X(2,I))**2 + (HY(K)-Y(2,I))**2)
      GO TO 90
  303 YY = SLO(I) * XX + B(I)
      RAD(N) = SQRT ((HX(K)-XX)**2 + (HY(K)-YY)**2)
```

RADIS

```
   90 CONTINUE
C
C        DETERMINE MINIMUM RADIUS FROM LIST CALCULATED ABOVE.
C
      IF (N - 1)196,304,196
  196 NNT=N-1
      RADMI=RAD(1)
      DO 91 NN = 1,NNT
      IF(RAD(NN+1)-RADMI) 315,91,91
  315 RADMI=RAD(NN+1)
   91 CONTINUE
      A(K)=RADMI-0.01
      GO TO 806
  304 A(K) = RAD(N) - 0.01
  806 CONTINUE
      RETURN
      END
```

PROFL

```
      SUBROUTINE PROFL (SLOPO,B,SLO,HX,HY,A,X)
C
C.......................................................................
C
C        SUBROUTINE PROFL
C
C         PURPOSE
C             1. TO DETERMINE THE TWO HORIZONTAL EXTREMITIES OF
C                THE SECTION BOUND BY THE CIRCULAR SLIP SURFACE.
C             2. CALCULATE LOWEST VERTICAL POSITION OF SLIP SURFACE.
C             3. CALCULATE SLICE WIDTH.
C
C.......................................................................
C
      DIMENSION SLOPO(1),B(1),SLO(1),HX(1),HY(1),A(1),X(2,1)
C
C         DIMENSIONS OF FOLLOWING VARIABLES MUST BE EQUAL OR
C              GREATER THAN 'NO. OF STRAIGHT LINES'.
      DIMENSION RX(200), RY(200)
      COMMON NUM,NOT,NU,KT,KEP
      COMMON FS,F,JPR
      COMMON NKK,NM,KK,JJ,KEPT,KJ
      COMMON N,NNT,NN,KEEP,JM,NNN
      COMMON I,L,K,NRETA,J,NNRET
      COMMON LINES,NTYES,LNS,NPHR,LNNS,NTYPE
      COMMON IN,IO,KOUNT,NRED,NBIS,NSIM
      COMMON YHI,EXTN,SLI,BSLI,XNEXT,YTN
      COMMON EXLO,YLO,EXHI,XRET,XMID
      COMMON RADL,ASLI,RADMI
      COMMON STEP,NCEN
      J=0.
C
C         DETERMINE THE TWO HORIZONTAL EXTREMITIES OF THE SECTION
C         BOUND BY THE CIRCULAR SLIP SURFACE.
C
      DO 6 I=1,LINES
C
      AQ= 1. + SLOPO(I)**2
      BQ = 2.*B(I)*SLO(I) - 2.*HX(K) - 2.*HY(K)*SLO(I)
      CQ = B(I)**2 - 2.*HY(K)*B(I) + HX(K)**2 +HY(K)**2-A(K)**2
      DQ = BQ**2 - 4.*AQ*CQ
      IF (DQ) 6,197,197
  197 PINTA=(-BQ-SQRT(DQ))/(2.*AQ)
      PINTB=(-BQ+SQRT(DQ))/(2.*AQ)
      IF(PINTA-X(1,I)) 101,183,183
  183 IF(PINTA-X(2,I)) 184,184,101
  184 J= J+1
      RX(J)=PINTA
      RY(J) = SLO(I)*RX(J) + B(I)
  101 IF(PINTB-X(1,I))6,185,185
  185 IF(PINTB-X(2,I))186,186,6
  186 J=J+1
      RX(J)=PINTB
      RY(J) = SLO(I)*RX(J) + B(I)
```

PROFL

```
    6 CONTINUE
      KEEP =2
      IF(J-1)142,142,635
  635 JM=J
      DO 31 NNN = 1,JM
      DO 30 N = 1,J
      IF(RX(N)-RX(KEEP))187,30,30
  187 KEEP=N
   30 CONTINUE
      IF (NNN - JM)198,134,198
  198 IF (NNN - 1) 199,199,133
  199 EXLO =RX(KEEP)
      YLO =RY(KEEP)
      RX(KEEP) = 100000.
      GO TO 31
  133 CCRX = RX(KEEP)
      CCRY = RY(KEEP)
      RX(KEEP) = 100000.
      GO TO 31
  134 EXHI = RX(KEEP)
      YHI  = RY(KEEP)
   31 CONTINUE
C         CALCULATE LOWEST VERTICAL POSITION OF SLIP SURFACE.
C
      IF(YHI-YLO) 630,631,631
  631 IF(HX(K)-EXLO)632,632,633
  633 EXTN=HX(K)
      YTN=HY(K)-A(K)
      GO TO 617
  632 EXTN=EXLO
      YTN=YHI
      GO TO 617
  630 IF(HX(K)-EXHI)615,616,616
  616 YTN=YHI
      EXTN=EXHI
      GO TO 617
  615 YTN=HY(K)-A(K)
      EXTN=HX(K)
  617 NUM=0.
      NOT = 0
      NU  = 0
C
C         CALCULATE SLICE WIDTH
C
      SLI = EXHI -EXLO
      BSLI = SLI / ASLI
  142 XNEXT = EXLO
      XRET  = XNEXT
      RETURN
      END
```

SLICE

```
      SUBROUTINE SLICE (X,SLO,B,HY,HX,A,JPROP,UNIWT,BUS,WIGHT,SINAP,SECA
     1P,TANAP,COBSL,TANPH,COSAP,PHI,COHES,RU)
C
C.......................................................................
C
C         SUBROUTINE SLICE
C
C          PURPOSE
C
C               TO CALCULATE THE PHYSICAL PARAMETERS OF EACH SLICE
C               WHICH ARE THEN TO BE EMPLOYED IN THE ANALYSIS OF
C               THE STABILITY OF A SLOPE BY THE CIRCULAR SLIP
C               SURFACE METHOD OF SLICES TECHNIQUE.
C
C.......................................................................
C
      DIMENSION BUS(1),WIGHT(1),SINAP(1),SECAP(1),TANAP(1)
      DIMENSION X(2,1),SLO(1),B(1),HY(1),HX(1),A(1),JPROP(1),UNIWT(1)
      DIMENSION COBSL(1),TANPH(1),COSAP(1),PHI(1),COHES(1)
      DIMENSION RU(1)
C
C          DIMENSIONS OF FOLLOWING VARIABLES MUST BE EQUAL TO OR
C          GREATER THAN 'LINES'.
      DIMENSION JPRPE(100),YDISC(100)
      DIMENSION YIN(100)
      COMMON NUM,NOT,NU,KT,KEP
      COMMON FS,F,JPR
      COMMON NKK,NM,KK,JJ,KEPT,KJ
      COMMON N,NNT,NN,KEEP,JM,NNN
      COMMON I,L,K,NRETA,J,NNRET
      COMMON LINES,NTYES,LNS,NPHR,LNNS,NTYPE
      COMMON IN,IO,KOUNT,NRED,NBIS,NSIM
      COMMON YHI,EXTN,SLI,BSLI,XNEXT,YTN
      COMMON EXLO,YLO,EXHI,XRET,XMID
      COMMON RADL,ASLI,RADMI
      COMMON STEP,NCEN
C
C          CALCULATE MID-POINT OF SLICE
C
  325 XNEXT = XNEXT + BSLI
      XMID = (XRET + XNEXT) /2.
      XRET = XNEXT
  120 YMU = 0.
      RFLAG=0.
C
C          CALCULATE MAXIMUM MID-POINT Y-COORDINATE OF SLICE
C
      DO 11 I=1,LNNS
      IF (XMID - X(1,I))  11,600,600
  600 IF (XMID - X(2,I))  123,123,11
  123 YMUM = SLO(I)*XMID + B(I)
      IF (YMUM -YMU)  11, 11,601
  601 YMU=YMUM
   11 CONTINUE
```

```
C
C         CALCULATE MINIMUM MID-POINT Y-COORDINATE OF SLICE
C
  121 AAG=1.
      BAG= 2.*HY(K)
      CAG= XMID**2 -2.*HX(K)*XMID +HX(K)**2 +HY(K)**2 -A(K)**2
      DAG= BAG**2 - 4.*CAG
      YML =(BAG -SQRT(DAG))/2.
      IF (YML -YMU) 602,700,700
  602 NUM =NUM+1
      YES = 0.
      KT = 0.
C
C         CALCULATE DEPTH AND MATERIAL TYPE OF EACH LAYER OF SLICE
C
      DO 13 I=1,LINES
      IF (XMID-X(1,I))  13,603,603
  603 IF (XMID-X(2,I)) 106,106,13
  106 YFOND = SLO(I)*XMID+B(I)
      IF(YFOND-YML)13,13,188
  188 IF(JPROP(I)-NTYPE)189,189,190
  190 YES=YFOND
      GO TO 13
  189 IF(YFOND-YMU)191,13,13
  191 IF (YFOND - YML)13,13,107
  107 KT = KT + 1
      JPRPE(KT)=JPROP(I)
      YIN(KT)=YFOND
   13 CONTINUE
C
C         NEXT STEP DEPENDS ON NUMBER OF LAYERS PRESENT IN SLICE
C
      IF (KT -1) 605,604,605
  604 YIN(2) =YIN(1) -1.
  605 KEP=2
      NKK =0.
      BUT =0.
      NM = 0.
      WEIGH = 0.
      IF (KT)108,143,108
  108 DO 15 N =1,KT
      IF (YIN(N)-YIN(KEP))  15,15,621
  621 KEP=N
   15 CONTINUE
  143 NKK = NKK + 1
      IF (NKK -1)607,606,607
  606 YINA=YMU
  607 IF ((KT+1)-NKK)110,110,109
  110 YIN(KEP) = YML
      KK = 0.
C
C         DETERMINE TYPE OF MATERIAL AT BASE OF SLICE
C
      DO 18 JJ=1,LNNS
```

```
      IF (XMID -X(1,JJ))  18,608,608
  608 IF (XMID -X(2,JJ)) 118,118,18
  118 YDISC(JJ) = SLO(JJ)*XMID + B(JJ)
      IF (YDISC(JJ) - YINA) 129,18,18
  129 KK = KK +1
      YDISC(KK) = YDISC(JJ)
      JPRPE(KK)=JPROP(JJ)
   18 CONTINUE
      IF (KK-1) 610,609,610
  609 YDISC(2) =YDISC(1) -1
  610 KEPT=2
      DO 19 KJ = 1,KK
      IF(YDISC(KJ)-YDISC(KEPT)) 19, 19,611
  611 KEPT=KJ
   19 CONTINUE
      JPR=JPRPE(KEPT)
      HSLI = YINA -YIN(KEP)
      GO TO 144
C
C         DETERMINE PHYSICAL PARAMETERS OF EACH LAYER
C
  109 HSLI = YINA -YIN(KEP)
      JPR=JPRPE(KEP)
  144 WEIGH=BSLI*UNIWT(JPR)*HSLI + WEIGH
      NOT  = NOT + 1
C
C         POREWATER PRESSURE CALCULATION
C
      BU = 0.
      IF (BUT) 131,612,131
C
C         DOES EITHER A PHREATIC OR WATER SURFACE EXIST
C
  612 IF(YES)135,613,135
  613 IF (UNIWT(JPR)-62.4)132,127,132
  132 BU = 0.
      GO TO 131
  127 BU = (YMU -YML) * BSLI * 62.4
      GO TO 131
  135 BU = (YES -YML) * BSLI * 62.4
      YES= 0.
  131 YINA = YIN(KEP)
      YIN(KEP) = 0.
  801 BUT=BU+BUT
  810 IF ((KT -NKK)) 111,143,108
  111 NU = NU + 1
C
C         DETERMINE WHETHER SLOPE OF EMBANKMENT IS POSITIVE
C         OR NEGATIVE.
C
      IF (YHI-YLO) 326,326,327
  326 HORIZ=HX(K)-XMID
      GO TO 811
  327 HORIZ=XMID-HX(K)
```

SLICE

```
C
C         SUMMARY OF PHYSICAL PARAMETERS OF EACH SLICE
C
  811 BUS(NU) = BUT + RU(JPR)*WEIGH
      WIGHT(NU)=WEIGH
      VERT = HY(K) - YML
      HYPOT = SQRT ((ABS(HORIZ))**2 + (ABS(VERT))**2)
      SINAP(NU)=HORIZ/HYPOT
      SECAP(NU)=HYPOT/VERT
      TANAP(NU)=HORIZ/VERT
      COBSL(NU)=COHES(JPR)*BSLI*144.
      TANPH(NU)=SIN(PHI(JPR)*0.017453)/COS(PHI(JPR)*0.017453)
      COSAP(NU)=1./SECAP(NU)
  700 CHECK = EXHI - XNEXT
      IF(CHECK -(0.5*BSLI)) 113,325,325
  113 CONTINUE
      RETURN
      END
```

BISH

```
       SUBROUTINE BISH(WIGHT,SINAP,COBSL,TANPH,BUS,SECAP,TANAP,HX,HY,A,CO
      1SAP)
C
C.....................................................................
C
C         SUBROUTINE BISHOP
C
C          PURPOSE
C              TO CALCULATE THE FACTOR OF SAFETY FOR THE STABILITY
C              OF A SLOPE WITH A CIRCULAR SLIP SURFACE BY
C              'BISHOP'S METHOD' AND/OR 'ORDINARY METHOD' OF SLICES.
C
C.....................................................................
C
      DIMENSION WIGHT(1),SINAP(1),COBSL(1),TANPH(1),BUS(1)
      DIMENSION SECAP(1),TANAP(1),HX(1),HY(1),A(1),COSAP(1)
      COMMON NUM,NOT,NU,KT,KEP
      COMMON FS,F,JPR
      COMMON NKK,NM,KK,JJ,KEPT,KJ
      COMMON N,NNT,NN,KEEP,JM,NNN
      COMMON I,L,K,NRETA,J,NNRET
      COMMON LINES,NTYES,LNS,NPHR,LNNS,NTYPE
      COMMON IN,IO,KOUNT,NRED,NBIS,NSIM
      COMMON YHI,EXTN,SLI,BSLI,XNEXT,YTN
      COMMON EXLO,YLO,EXHI,XRET,XMID
      COMMON RADL,ASLI,RADMI
      COMMON STEP,NCEN
  505 FORMAT (1X,T2,F7.2,T12,F7.2,T31,F7.1,
     1         T44,F7.1,T52,F7.1,T62,F7.1,T70,F7.1,
     2         T80,F7.1,T87,F7.1,T100,F7.3,T111,F7.3)
      IF (HY(K)) 638,638,641
  641 IF (J-1) 638,638,637
  638 EXLO=0.
      YLO=0.
      EXHI=0.
      YHI=0.
      EXTN=0.
      YTN=0.
      FS=1000.
      F=1000.
      GO TO 620
  637 IF(NBIS)618,618,181
  181 WSINA=0.
      COMBI=0.
      FST = 1.
C
C          RE-ITERATION EQUATION TO CALCULATE FACTOR OF SAFETY
C          BY 'BISHOP'S METHOD'.
C
   17 DO 16 N=1,NU
      WSINA = WSINA + (WIGHT(N) *SINAP(N))
      CBTNW = COBSL(N) +TANPH(N) *(WIGHT(N)-BUS(N))
      ENDTE = SECAP(N) /(1.+ TANAP(N)*TANPH(N)/FST)
      COMBI = COMBI + CBTNW * ENDTE
```

BISH

```
   16 CONTINUE
  117 FS = COMBI /WSINA
      IF(FS)622,116,622
  622 COMBI =0.
      WSINA =0.
      IF(FS-FST) 114,114,614
  614 IF((FS-FST)-0.001) 116,116,115
  114 IF((FST-FS)-0.001) 116,116,115
  115 FST = FS
      GO TO 17
  618 FS=1000.
C
C        EQUATION TO CALCULATE FACTOR OF SAFETY BY
C        'ORDINARY METHOD'.
C
  116 IF (NSIM) 619,619,192
  192 CBTNW= 0.
      WSINA= 0.
      DO 26 N = 1,NU
      WSINA=WSINA +(WIGHT(N)*SINAP(N))
      CBTNW=CBTNW +COBSL(N)*SECAP(N) +TANPH(N)*(WIGHT(N)*
     1COSAP(N)-BUS(N)*SECAP(N))
   26 CONTINUE
      F=CBTNW/WSINA
      GO TO 620
  619 F =1000.
  620 WRITE(IO,505)HX(K),HY(K),A(K),EXLO,YLO,EXHI,YHI,EXTN,YTN,F,FS
      RETURN
      END
```

JANPA

```
      SUBROUTINE JANPA(JPROP,X,Y,SLO,B,UNIWT,BUS,WIGHT,TANAT,TANAP,
     J                 TANPH,COHES,CSAPS,COBSL,DTO,RU,PHI,DEPDN,XRI)
C
C.......................................................................
C
C        SUBROUTINE JANPA
C
C         PURPOSE
C              TO CALCULATE THE PHYSICAL PARAMETERS OF EACH SLICE
C              WHICH ARE THEN TO BE EMPLOYED IN THE ANALYSIS FOR
C              THE STABILITY OF A SLOPE BY THE NON-CIRCULAR SLIP
C              SURFACE METHOD OF SLICES TECHNIQUE.
C
C         REMARKS
C              1. SLIP SURFACE IS DEFINED BY A SERIES OF STRAIGHT
C                 LINES WHICH POSSESS THE TYPE NUMBER 'NNTYE'.
C                 NNTYE = NTYPE + 1
C              2. THRUST LINE IS DEFINED BY A SERIES OF STRAIGHT
C                 LINES WHICH POSSESS THE TYPE NUMBER 'NNTRU'.
C                 NNTRU = NTYPE + 2
C                 NOTE. A TYPE NUMBER MUST ALWAYS BE ASSIGNED FOR
C                               THE THRUST LINE.
C                       IF A THRUST LINE IS NOT DEFINED BY A SERIES
C                               OF STRAIGHT LINES, A HORIZONTAL THRUST
C                               LINE IS ASSUMED.
C              3. PHREATIC SURFACE IS DEFINED BY A SERIES OF STRAIGHT
C                 LINES.
C                 IF 'NPHR' = 1, A PHREATIC SURFACE IS ASSUMED TO EXIST.
C                 IF 'NPHR' = 0, NO PHREATIC SURFACE IS ASSUMED TO EXIST.
C
C         DEFINITIONS
C              DEPDN = VERTICAL DEPTH OF SLICE ON DOWNWARD SIDE
C              NTYPE = TOTAL NUMBER OF MATERIAL TYPES
C              NNTYE = TYPE NUMBER ASSIGNED TO SLIP SURFACE
C              NNTRU = TYPE NUMBER ASSIGNED TO THRUST LINE
C              NTYES = TOTAL NUMBER OF TYPES
C
C
C
C.......................................................................
C
      DIMENSION JPROP(1),X(2,1),Y(2,1),SLO(1),B(1),UNIWT(1),BUS(1)
      DIMENSION WIGHT(1),TANAT(1),TANAP(1),TANPH(1),COHES(1),CSAPS(1)
      DIMENSION COBSL(1),DTO(1),RU(1),PHI(1)
      DIMENSION DEPDN(1),XRI(1)
C
C        DIMENSIONS OF FOLLOWING VARIABLES MUST BE EQUAL TO OR
C        GREATER THAN 'LINES'.
      DIMENSION YIN(100),YDISC(100),JPRPE(100)
      COMMON NUM,NOT,NU,KT,KEP
      COMMON FS,F,JPR
      COMMON NKK,NM,KK,JJ,KEPT.KJ
      COMMON N,NNT,NN,KEEP,JM,NNN
      COMMON I,L,K,NRETA,J,NNRET
```

JANPA

```
      COMMON LINES,NTYES,LNS,NPHR,LNNS,NTYPE
      COMMON IN,IO,KOUNT,NRED,NBIS,NSIM
      COMMON YHI,EXTN,SLI,BSLI,XNEXT,YTN
      COMMON EXLO,YLO,EXHI,XRET,XMID
      COMMON RADL,ASLI,RADMI
      COMMON STEP,NCEN
      COMMON NJAN
  400 FORMAT (2X,8(F10.2,2X))
      EXLO=100000.
      EXHI=-100000.
      NTYPE=NTYES-NPHR-2
      NNTYE=NTYES-NPHR-1
      NNTRU=NTYES-NPHR
C
C        DETERMINE THE TWO HORIZONTAL EXTREMITIES OF THE SECTION
C        BOUND BY THE NON-CIRCULAR SLIP SURFACE.
C
      DO 1 I=1,LNNS
      IF (JPROP(I) - NNTYE) 1,2,1
    2 XLO = X(1,I)
      XHI = X(2,I)
      IF (XLO - EXLO)3,4,4
    3 EXLO =XLO
      YLO  =Y(1,I)
    4 IF (XHI-EXHI)1,1,5
    5 EXHI=XHI
      YHI= Y(2,I)
    1 CONTINUE
C
C        DETERMINE SLICE WIDTH
C
      BSLI= (EXHI-EXLO)/ASLI
      IF (BSLI) 74,74,201
  201 NUM = 0
      NOT =0
      NU =0
      COUN=0.
C
C        DETERMINE WHETHER THE SLOPE OF THE EMBANKMENT IS POSITIVE
C        OR NEGATIVE
C
      IF (YHI-YLO) 110,110,120
  120 XMID =EXHI + (BSLI/2.)
  130 COUN = COUN +1.
      XMID = XMID -2.* BSLI
      GO TO 150
    6 IF (YHI-YLO) 140,140,131
  110 XMID = EXLO - (BSLI/2.)
  140 COUN = COUN + 1.
      GO TO 150
  131 COUN = COUN + 1.
      XMID = XMID - 2.* BSLI
  150 TANRE = 0.
      TANRT=0.
```

```
      YMU = 0.
      XMID =XMID +BSLI
C
C        DETERMINE MINIMUM AND MAXIMUM Y-COORDINATES OF HORIZONTAL
C        MID-POINT OF SLICE.
C
      DO 7 I=1,LNNS
      IF (JPROP(I) - NNTYE) 8,7,7
    8 IF (XMID - X(1,I)) 7,11,11
   11 IF (XMID - X(2,I)) 12,12,7
   12 YMUM = SLO(I) * XMID + B(I)
      IF (YMUM - YMU) 7,7,13
   13 YMU = YMUM
    7 CONTINUE
C
C        DETERMINE ANGLE AT WHICH THE INTER-SLICE FORCE ACTS
C        ON THE DOWNWARD SIDE OF SLICE
C
      IF (YHI - YLO) 170,170,160
  160 XRIGH =XMID - BSLI/2.
      GO TO 180
  170 XRIGH = XMID +BSLI/2.
  180 DO 101 I=1,LNNS
      IF (JPROP(I)-NNTRU)101,102,101
  102 IF (XRIGH - X(1,I)) 101,105,106
  106 IF (XRIGH - X(2,I)) 107,105,101
  107 TANRT = SLO(I)
      GO TO 101
C
C        TEST HORIZONTAL POSITION OF DOWNWARD SIDE OF SLICE.
C        IF THIS POSITION IS EXACTLY AT THE INTERSECTION OF
C        TWO THRUST LINES, THEN THE ASSUMPTION IS MADE THAT
C        THE RESULTANT ANGLE IS THE MEAN OF THE TWO IMPLIED
C        ANGLES.
C
  105 TANRT= SLO(I)/2. +TANRT
  101 CONTINUE
C
C        DETERMINE WHICH SLIP SURFACE LINE IS AT MID-POINT
C        OF SLICE
C
      DO 20 I=1,LNNS
      IF (JPROP(I) -NNTYE) 20,21,20
   21 IF (XMID-X(1,I)) 20,24,22
   22 IF (XMID - X(2,I)) 23,24,20
   23 YML=SLO(I) *XMID +B(I)
      TANRE = SLO(I)
      GO TO 20
   24 TANRE = SLO(I) /2. + TANRE
      YML = SLO(I) * XMID + B(I)
   20 CONTINUE
      NUM = NUM +1
      YES= 0.
      KT=0
```

JANPA

```
C
C         DETERMINE NUMBER OF LAYERS IN SLICE
C
      DO 33 I=1,LINES
      IF (XMID -X(1,I)) 33,34,34
   34 IF (XMID -X(2,1)) 35,35,33
   35 YFOND =SLO(I) * XMID + B(I)
      IF (YFOND -YML) 33,33,36
   36 IF (JPROP(I) - NNTRU) 25,25,38
   38 YES=YFOND
      GO TO 33
   25 IF (JPROP(1) - NTYPE) 37,37,33
   37 IF(YFOND -YMU) 39,33,33
   39 IF (YFOND - YML) 33,33,41
   41 KT=KT+1
      YIN(KT)=YFOND
      JPRPE(KT)=JPROP(I)
   33 CONTINUE
      IF (KT-1) 42,43,42
   43 YIN(2) =YIN(1) - 1.
   42 KEP = 2
      NKK= 0
      BUT= 0.
      NM = 0
      WEIGH=0.
      VERCO= 0.
C
C         DETERMINE PHYSICAL PARAMETERS OF EACH LAYER OF SLICE
C
      IF(KT) 44,45,44
   44 DO 46 N=1,KT
      IF (YIN(N) -YIN(KEP))46,46,47
   47 KEP=N
   46 CONTINUE
   45 NKK =NKK+1
      IF(NKK -1) 48,49,48
   49 YINA =YMU
   48 IF ((KT+1)-NKK) 50,50,51
   50 YIN(KEP) =YML
      KK=0
C
C         DETERMINE MATERIAL TYPE AT BASE OF SLICE
C
      DO 52 JJ=1,LNNS
      IF (JPROP(JJ)-NTYPE) 26,26,52
   26 IF (XMID-X(1,JJ)) 52,53,53
   53 IF (XMID-X(2,JJ)) 54,54,52
   54 YDISC(JJ) = SLO(JJ) * XMID + B(JJ)
      IF (YDISC(JJ)- YINA ) 55,52,52
   55 KK=KK+1
      YDISC(KK)=YDISC(JJ)
      JPRPE(KK)=JPROP(JJ)
   52 CONTINUE
      IF (KK-1) 56,57,56
```

```
   57 YDISC(2) = YDISC(1) - 1.
   56 KEPT = 2
      DO 58 KJ=1,KK
      IF (YDISC(KJ)-YDISC(KEPT)) 58,58,59
   59 KEPT =KJ
   58 CONTINUE
      JPR =JPRPE(KEPT)
C
C         DETERMINE HEIGHT OF LAYER
C
      HSLI = YINA - YIN(KEP)
      GO TO 60
   51 HSLI = YINA -YIN(KEP)
      JPR = JPRPE(KEP)
   60 WEIGH=BSLI *UNIWT(JPR)*HSLI + WEIGH
      VERCO = VERCO + 144.*HSLI*COHES(JPR)
      NOT =NOT +1
      BU = 0.
      IF (BUT) 68,62,68
   62 IF (YES) 63,64,63
   64 IF (UNIWT(JPR) -62.4) 65,66,65
   65 BU=0.
      GO TO 67
   66 BU=(YMU-YML)*BSLI *62.4
      GO TO 67
   63 BU=(YES-YML)*BSLI *62.4
      YES=0.
   67 YINA=YIN(KEP)
      YIN(KEP)=0.
   69 BU = RU(JPR) * WEIGH + BU
   68 BUT = BU +BUT
      IF (KT-NKK) 70,45,44
C
C         SUMMARY OF COMPUTED PARAMETERS FOR EACH SLICE
C
   70 NU =NU +1
      BUS(NU)= BUT
      WIGHT(NU)=WEIGH
C
C         DETERMINE WHETHER SLOPE OF EMBANKMENT IS POSITIVE
C         OR NEGATIVE
C
      IF(YHI-YLO)71,71,72
   71 TANAP(NU)= -TANRE
      TANAT(NU)= -TANRT
      GO TO 73
   72 TANAP(NU)=TANRE
      TANAT(NU)=TANRT
   73 CSAPS(NU) = 1./(1.+TANRE*TANRE)
      TANPH(NU)=SIN(PHI(JPR)*0.017453)/COS(PHI(JPR)*0.017453)
      COBSL(NU)=COHES(JPR)* BSLI *144.
      DTO(NU) =0.
      DEPDN(NU) = VERCO
      XRI(NU) = XRIGH
```

JANPA

```
   IF(ASLI -COUN) 74,74,6
74 CONTINUE
   RETURN
   END
```

JANCA

```
      SUBROUTINE JANCA(WIGHT,DTO,TANAP,BUS,TANPH,CSAPS,TANAT,COBSL,DEPDN
     S,XRI)
C
C.......................................................................
C
C       SUBROUTINE JANCA
C
C        PURPOSE
C             TO CALCULATE THE FACTOR OF SAFETY OF AN EMBANKMENT
C             OR SLOPE EMPLOYING A NON-CIRCULAR SLIP SURFACE
C             METHOD OF SLICES TECHNIQUE
C
C        DEFINITIONS
C             SDEO(N) = HORIZONTAL INTER-SLICE FORCE
C             SDTO(N) = VERTICAL INTER-SLICE FORCE
C
C.......................................................................
C
      DIMENSION WIGHT(1),DTO(1),TANAP(1),BUS(1),TANPH(1)
      DIMENSION CSAPS(1),TANAT(1),COBSL(1)
      DIMENSION DEPDN(1),XRI(1)
C
C        DIMENSIONS OF FOLLOWING VARIABLES MUST BE GREATER THAN OR
C              EQUAL TO 'NO. OF SLICES'.
      DIMENSION SNALP(100),WTANA(100),SDEO(100)
      DIMENSION DEO(100),REQFR(100),SDTO(100)
      COMMON NUM,NOT,NU,KT,KEP
      COMMON FS,F,JPR
      COMMON NKK,NM,KK,JJ,KEPT,KJ
      COMMON N,NNT,NN,KEEP,JM,NNN
      COMMON I,L,K,NRETA,J,NNRET
      COMMON LINES,NTYES,LNS,NPHR,LNNS,NTYPE
      COMMON IN,IO,KOUNT,NRED,NBIS,NSIM
      COMMON YHI,EXTN,SLI,BSLI,XNEXT,YTN
      COMMON EXLO,YLO,EXHI,XRET,XMID
      COMMON RADL,ASLI,RADMI
      COMMON STEP,NCEN
      COMMON NJAN
  299 FORMAT('1',5X,'SUMMARY OF INTER-SLICE FORCES ON DOWNWARD SIDE OF D
     1ESIGNATED SLICES   ---   ITERATION NO. ',I2)
  300 FORMAT (/,5X,'SLICE NUMBER',5X,'HOR. COMPONENT',
     1        5X,'VERT. COMPONENT',5X,'REQD. FRICTION ANGLE',
     2        5X,'HOR. POS. OF I-S FORCE')
  301 FORMAT(11X,I2,12X,F10.2,9X,F10.2,8X,F12.2,14X,F10.2)
  302 FORMAT (/,7X,'FACTOR OF SAFETY =',F8.3)
  303 FORMAT(/,1X,'FINAL FACTOR OF SAFETY =',F8.3)
  400 FORMAT (2X,6(F12.2,2X))
  603 FORMAT ('1',//,10X,'INPUT DATA IN ERROR')
      KKTT=0
      FO =1.
C
C        APPROXIMATE SOLUTION
C
      IF (BSLI) 601,601,600
```

JANCA

```
  600 NIT = 0
  208 WTANS =0.
      SNALS=0.
      NIT = NIT + 1
      DO 200 N =1,NU
      WTANA(N) = (WIGHT(N)-DTO(N))* TANAP(N)
      SHEAR = COBSL(N) + (WIGHT(N)-DTO(N)-BUS(N))* TANPH(N)
      ONECS = CSAPS(N) * (1.+ TANAP(N) * TANPH(N) / FO)
      SNALP(N) = SHEAR / ONECS
  200 CONTINUE
      KKTT=KKTT +1
      DO 201 N=1,NU
      WTANS=WTANS +WTANA(N)
  201 SNALS= SNALS +SNALP(N)
      FST= SNALS /WTANS
      IF(KKTT-1)209,209,210
  210 DIF=ABS(FST-FO)
      IF(DIF -0.001) 211,211,209
C
C         RIGOROUS SOLUTION
C
  209 FO= FST
      DO 202 N=1,NU
      DEO(N)= WTANA(N) -SNALP(N) /FO
      IF(N-1)203,203,204
  203 SDEO(N) = DEO(N)
      GO TO 202
  204 SDEO(N)= SDEO(N-1) + DEO(N)
  202 CONTINUE
      DO 205 N=1,NU
      SDTO(N)= SDEO(N) * TANAT(N)
      IF(N-1) 206,206,207
  206 DTO(N) =SDTO(N)
      GO TO 215
  207 DTO(N) =SDTO(N)-SDTO(N-1)
C
C         CALCULATE REQUIRED VERTICAL ANGLE OF INTERNAL FRICTION
C
  215 DIFF = ABS(SDTO(N)) - DEPDN(N)
      IF (DIFF) 216,216,217
  216 REQ =0.
      GO TO 218
  217 REQ = DIFF /ABS(SDEO(N))
  218 REQFR(N) = ATAN(REQ) / 0.017453
  205 CONTINUE
      WRITE (IO,299) NIT
      WRITE(IO,300)
      DO 220 N=1,NU
      WRITE(IO,301)N,SDEO(N),SDTO(N),REQFR(N),XRI(N)
  220 CONTINUE
      WRITE(IO,302)FST
      GO TO 208
  211 WRITE (IO,303) FST
      GO TO 602
```

JANCA

```
601 WRITE (IO,603)
602 CONTINUE
    RETURN
    END
```

APPENDIX "B"

PNEUMATIC PIEZOMETER CALIBRATION CURVES

PNEUMATIC

PIEZOMETER

Calibration Curves

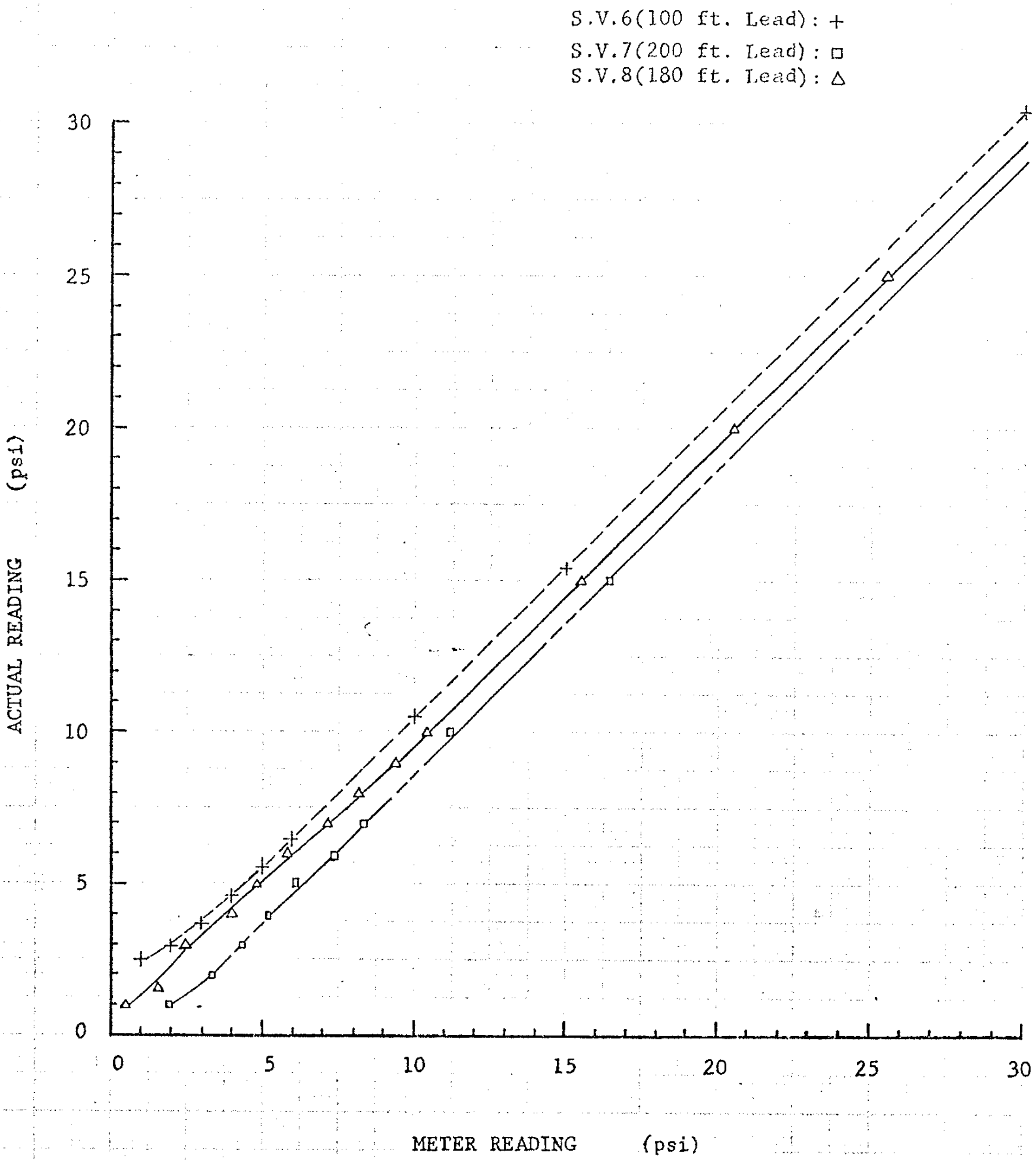

Figure 23

PNEUMATIC
PIEZOMETER
Calibration Curves

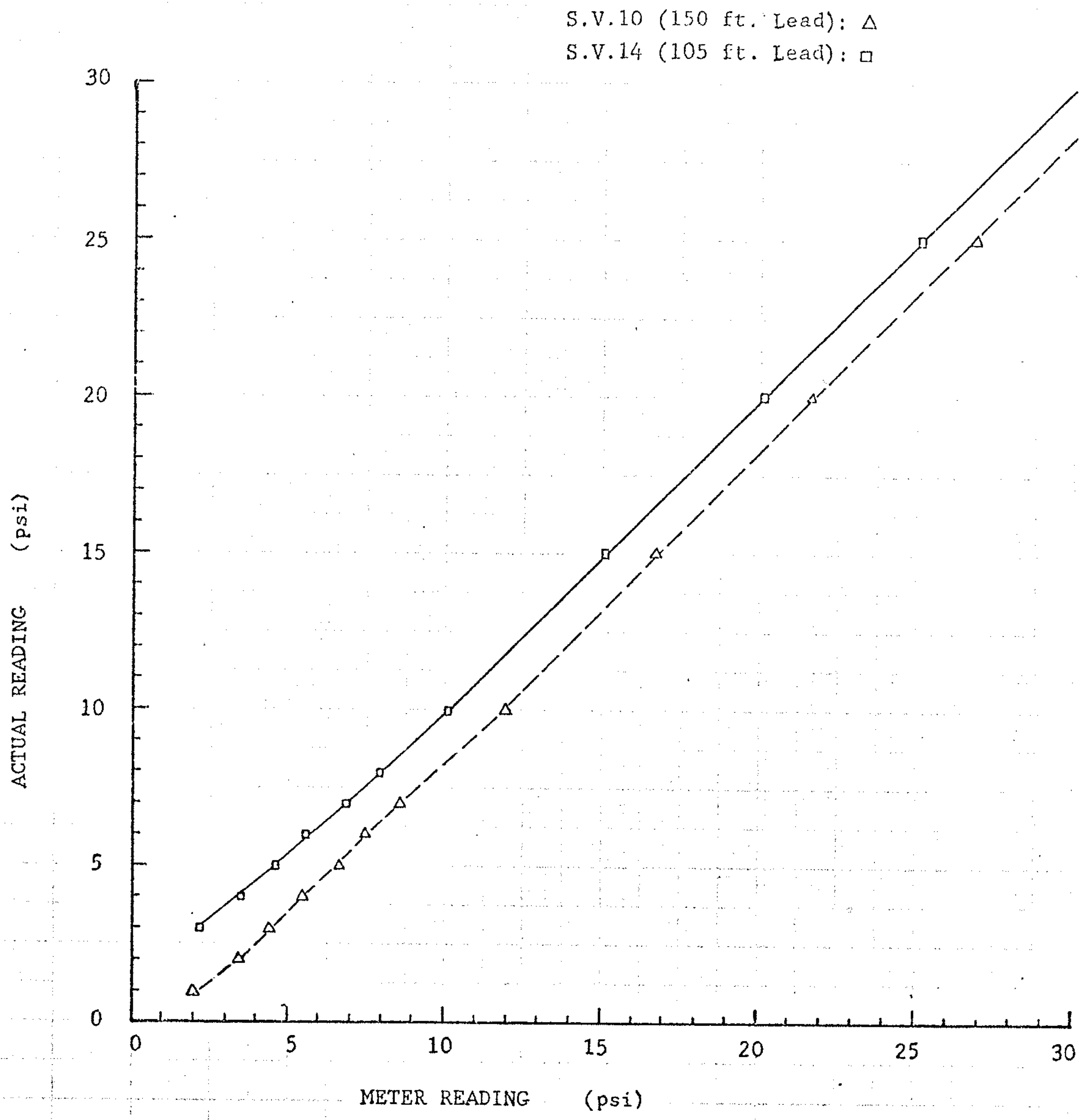

Figure 24

APPENDIX "C"

GENERAL REVIEW
OF VARIOUS
PIEZOMETER TYPES

Numerous types of piezometers have been developed and improved by various agencies in recent years in an attempt to acquire an instrument that is capable of giving accurate readings with a minimum time lag and at a reasonable cost. The most desired features of a piezometer as summarized by SCOTT and KILGOUR[22] are: (1) ruggedness, (2) simplicity, (3) ease of installation, (4) minimum maintenance, (5) long life, (6) low cost, (7) small volume factor (implies small time lag), (8) the ability to exclude air and gas from the measuring system, and (9) insensitiveness to temperature. Other factors that have been found desirable are: (10) ease of acquiring measurements and (11) sensitivity. The types of piezometers currently employed are (1) open standpipe, (2) Casagrande type, (3) metallic "Geonor", (4) hydraulic, (5) electrical, (6) vibrating wire, and (7) the pneumatic type.

The basic problem of any simple piezometer is that the energy required to operate it prevents the instrument from recording an immediate change. For a given pressure change this energy is proportional to the volume of pore water that must flow into the instrument, which accounts for the fact that the greatest time lag occurs in the open standpipe type piezometer. The relatively large diameter of this type of piezometer causes large time lags in moderately impervious soils. The construction of this type of piezometer can vary from an open observation well to a small diamter pipe. Pore pressure readings are most easily made by measuring the head of water in the pipe by an electrical probe. The time lag can be reduced by using a small diameter pipe and by providing ample communication between the piezometer tip and ambient low impervious clay material by installing a large collecting volume of porous material around the tip. The advantages of this type of piezometer are its simplicity, ruggedness, and over-all reliability.

The Casagrande type piezometer as described by BOZOZUK[23] is actually a refined version of the open-stand pipe tube. It consists of a porous stone tip embedded in sand in a sealed portion of a boring, and connected to the surface with a 3/8 inch diameter plastic tube. The electrical probe is the usual device used to measure the head of water in the tube. If the porewater pressures are so great that the water is forced out the top, a Bourdon gauge manometer can be used to measure the excess pore water pressure. The time lag is generally less than in the former type due to the reduction in required volume change, but is still quite significant in highly impervious clays. It has been proven quite successful for many materials and its non-metallic construction gives it a corrosive resistant quality. Its success is demonstrated by the fact that the reliability of unproven piezometers is usually evaluated on the basis of how well the results agree with those of the Casagrande type. One of the greatest disadvantages of this type of piezometer is the time required for its installation. The most time-consuming job is the preparation and installation (particularly the tamping) of the bentonite seal. But this installation time can be reduced if an AM-9 gel seal is used as described by BOZOZUK[23].

The metallic "Geonor" piezometer which is discussed in detail by BOZOZUK[23] was developed by the Norwegian Geotechnical Institute. It consists of a porous metallic tip coupled to a steel "E" size drill rod and then forced into the clay soil to the required elevation. Water pressures at the point are read by measuring the head of water in a polyethylene tube connected through the drill rods to the porous tip. This unit is simple, compact, quickly assembled, and easily installed. These piezometers can also be withdrawn, cleaned, and re-used. Its main disadvantage is that its metallic construction is susceptible to corrosive clay soils.

The hydraulic type piezometer is of a more complex nature and is used mainly in major dam projects. The piezometer consists of a collection chamber connected directly to a pressure gauge near the downstream face of the dam. It requires long tubing lines, expensive and complex gauge houses and careful techniques during installation and operation. This type of instrumentation as documented by the U.S. BUREAU of RECLAMATION[24] is not feasible for small projects.

Electrical piezometers are extremely sensitive devices, have negligible time lag, and are suitable for measuring ground water and pore pressure fluctuations in materials exhibiting low permeability. In addition to eliminating problems of line freezing, the electrical apparatus offers the possibility of remote monitoring, electronic data accumulation, and reduction. The unit consists of a tip having a diaphragm that is deflected by the pore pressure against one face, and is measured by means of electrical transducers. The time lag of this type of instrument is negligible because it consists of a relatively stiff diaphragm which requires only a minute volume change to bring the instrument in equilibrium with the new pore pressure. If reliable readings are to be obtained the measuring system must have no zero drift of electronic parts, good calibration stability, and should not experience any effect due to change in voltage supply or circuit resistance. Electrical piezometers are not recommended for installation in embankments where reliable readings are required over an extended period of time, due to its inability to withstand severe environmental problems, and to its relatively short structural life. BROOKER, SCOTT, and ALI[25] have recommended that the use of electrical instruments not be used in partially saturated soils, as difficulties are experienced in de-airing and flushing the units.

The basic principal of the vibrating wire piezometer is that the natural frequency of vibration of a certain length of stretched wire is dependent on the tension in the wire. The wire is stretched between two points on a diaphragm and any strain developed in the diaphragm causes strain in the wire. The change in the stress caused by the change in strain in the wire can be recorded by measuring the change in its natural frequency. Suitable calibration of an instrument will relate the value of the pressure to the frequency of the vibration of the wire. SCOTT and KILGOUR[22] give a detailed description of the MAIHAK vibrating wire piezometer and its operation. They found from their tests that the leads from the instrument to the measuring meter are subject to stresses from soil deformation and therefore are the weakest links in the piezometer system. Another disadvantage is that great care is required to install this type of instrument. But the time lag is negligible due to the small volume change required to activate the stiff diaphragm. Its advantages over strictly electrical strain gauges are as follows:

(1) Change in the properties of the electrical circuit does not alter the measuring gauge and its frequency.

(2) Readings are independent of fluctuations in the power input, current, capacitance, change in electrical re-

sistance of the circuit, or induction from ground circuits.

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