THE EFFECT OF SHEAR STRENGTH AND PORE PRESSURE DISTRIBUTION ON THE STABILITY OF SLOPES

by

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SYNOPSIS

The analysis of the stability of slopes in eastern Canada requires a better understanding of the behaviour of the Champlain Sea clays in the low to very low stress range. Recent literature indicates that the shear strength-normal stress relationship for these soils, as given by the Mohr-Coulomb failure envelope, is curved in the low to intermediate stress range. The importance of the groundwater flow conditions has been emphasized since the type of flow can considerably vary from one site to another. The applicability of Bishop's modified method for slope stability analysis in the Ottawa area clay slopes has been demonstrated and the method is widely accepted by researchers and practising engineers.

The slope stability behaviour of Leda clay and the representation of its shear properties are investigated in the very low stress range by a parametric study using a computer program developed by the author. This program, based on the Bishop modified expression, takes into account an approximation of the soil's curved failure envelope, as well as factual groundwater flow. The program is well documented and typical analysis encountered in engineering

problems are run. Two versions of the program are offered: a comprehensive Fortran program adapted to an IBM 360, and a simplified version written for a minicalculator (TI-59). The parametric study examines various combinations of soil strength parameters and groundwater flow conditions for set slope geometries. A general relationship between the slope geometry and the groundwater flow type is suggested.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

u	Pore pressure
u_w	Pore water pressure
σ_n	Normal stress
σ_n'	Effective normal stress
σ_1	Major principal stress
σ_2	Intermediate principal stress
σ_3	Minor principal stress
τ	Shear strength
τ'	Effective shear strength
γ	Unit weight of soil
γ_s	Unit weight of saturated soil
γ_w	Unit weight of water
w	Water content
w_L	Liquid limit
w_P	Plastic limit
I_w	Plasticity index
I_L	Liquidity index
c'	Effective cohesion intercept
ϕ'	Effective apparent angle of internal friction

LIST OF APPENDICES

1- INTRODUCTION

1.1 General

The following is a two part study encompassing the development of a slope stability computer program and the analysis of slopes considering different shear strength envelopes of clayey soils in the very low stress range. The influence of the very low stress shear strengths as well as of various groundwater flow regimes on the stability of slopes is investigated using the developed computer program.

At present, information describing the behaviour in shear under very low stresses of the Champlain Sea clays is limited. Failure envelopes for some Eastern Canada clays are available in the literature but are incomplete due to the inapplicability of the present testing procedures in the very low stress range. Furthermore, the Mohr-Coulomb theory does not adequately describe the curved envelopes shown by these soils.

Presently known computer programs for slope stability analysis contain no facilities for dealing with stress dependant shear strengths. The method for handling porepressures normally requires an intermediate step to transform the flow net data into a series of piezometric surfaces or into a grid of equipotential values.

1.2 Statement of Problem

A comprehensive study of the stability of slopes in Champlain Sea clays raises two questions in order to adequately define the problem:

1- what is the influence of varying low stress range shear strength characteristics, and

2- what is the influence of varying the type of groundwater flow regime on the computed factor of safety?

These questions can be answered in practise by determining the degree of precision required from field observations and laboratory testing to adequately formulate the parameters controlling the stability of a slope.

Since a slope stability analysis normally requires the investigation of a large number of failure circles for a given data set, a comprehensive user oriented computer program is necessary. This program should be sufficiently well documented to allow an understanding of the techniques used, since the user is responsible for the results obtained. It should furthermore use a data input format similar to the results obtained from field observations and laboratory testing.

The program itself should be simple enough to allow modifications and adaptation to the mini-calculators used in engineering consultants offices. The method of analysis should be one which is known to be applicable to the problem at hand.

1.3 Objectives of the Study

Since none of the slope stability analysis programs known to the author present the above characteristics, the first objective of this study is to develop a computer program offering the features discussed in the previous section.

The parametric study done using the developed computer program takes into consideration slope geometries representative of those observed in the Ottawa area. Realistic porewater pressure distributions, as well as those normally assumed in standard analysis, are discussed. The shear behaviour of three local clays and its effect on the stability of slopes by varying the above mentioned parameters are examined. The results obtained are compared with the factors of safety resulting from the use of the parameters normally used in a geotechnical investigation.

1.4 Thesis Outline

The following is a chapter by chapter summary of the thesis.

Chapter 2 - discusses the general geological and geotechnical properties of the Champlain Sea clay deposits.

Chapter 3 - reviews the classical Mohr-Coulomb theory and presents the general shear characteristics of the Leda clay deposits. The Bishop modified expression is also reviewed considering a multilinear model of the Champlain Sea clay curved failure envelope.

Chapter 4 - is a detailed description of the geology, stratigraphy, geochemical, hydrological and geotechnical characteristics of the deposits at the three example sites.

Chapter 5 - discusses the conditions for the parametric analysis, describing in detail the slope geometries, soil properties and groundwater flow systems assumed.

Chapter 6 - presents a complete description of the computer program. A short discussion of other available programs is also presented.

Chapter 7 - presents and discusses the results of the parametric analysis. The significance of these results is examined.

Chapter 8 - summarises this study and its main conclusions. Some suggestions for further studies are also given.

CHAPTER 2

GEOLOGY OF THE CHAMPLAIN SEA DEPOSITS

2.1 Outlook

A marine invasion of the then Champlain Valley, formed following the retreat of the Wisconsin glaciers, resulted in the deposition a thick succession of unconsolidated marine sediments on the Ottawa - St.Lawrence Lowlands. These sediments consist mainly of the two types of silty clay deposits: a major intact clay horizon which is overlain in Eastern Ontario by a wedge of fissured clay material.

This chapter presents a general discussion of the geology and extent of these deposits, as well as a brief review of the properties of the two Champlain Sea clays as observed in the Ottawa area.

2.2 General Geology

Near the end of the Wisconsin glaciation period, the weight of the recessing ice sheet left a deep depression within the northern part of the North American continent. As the ice front regressed, this depression, the Champlain Valley, was inundated by a late shallow marine transgression.

Both the glaciation period and the Champlain Sea invasion are recorded in Eastern Canada by the characteristic topographies and sediments resulting from these events.

Evidence for glacial erosion is found in the irregular topography of the Canadian Shield, while evidence for glacial and fluvio-glacial deposition is found in the basal tills, sands, gravels and lacustrine clays. The marine sediments were probably derived from the reerosion of the previous deposits and were redeposited in deltaic, beach and brackish environments (Wilson, 1965).

Although little is known of the exact sequence of events during the retreat of the Wisconsin ice sheet, local fluctuating readvances of the ice front probably occurred, causing a disturbance of some of the Champlain Sea sediments (Richard, 1975a).

The Champlain Sea was a late glacial marine invasion which was followed by estuarine and lacustrine periods due to the isostatic readjustment of the continental crust. During this uplift period, from approximately 13,000 to 8,000 B.P. (Richard, 1975a; Karrow, 1961), the land rose more than 700 feet through isostatic rebound (Kenney, 1964).

The maximum sea depth in the Ottawa area has been estimated at several hundred feet.

The materials deposited in this shallow sea environment were in all probability initially derived from fluvial erosion of the land immediately adjacent to the retreating ice tongues. Deltaic type sand and gravel deposits were formed at river outlets while the finer fractions sedimented in quieter environments farther from shore. Shoreline erosion sorted out beach sediments and, with underwater slumping, created further variations in the final sedimentary deposits (Crawford, 1968). The extent of the Champlain Sea deposits is indicated in Figure 2.1.

In more recent times, the downgrading Ottawa river has cut erosinal terraces in the Champlain Sea deposits, exposing nodes of glacial drift and Ordovician bedrock which probably formed shoals during the marine period. Downstream from these exposed areas, the clay terraces are usually mantled by a thin cover of alluvial sand. Massive slope failures and land movements are actually taking place and modifying the gently sloping clay plain topography (Richard, 1975a & b).

This extensive clay deposit, to which this study devotes a particular interest, has been referred to as "Le-

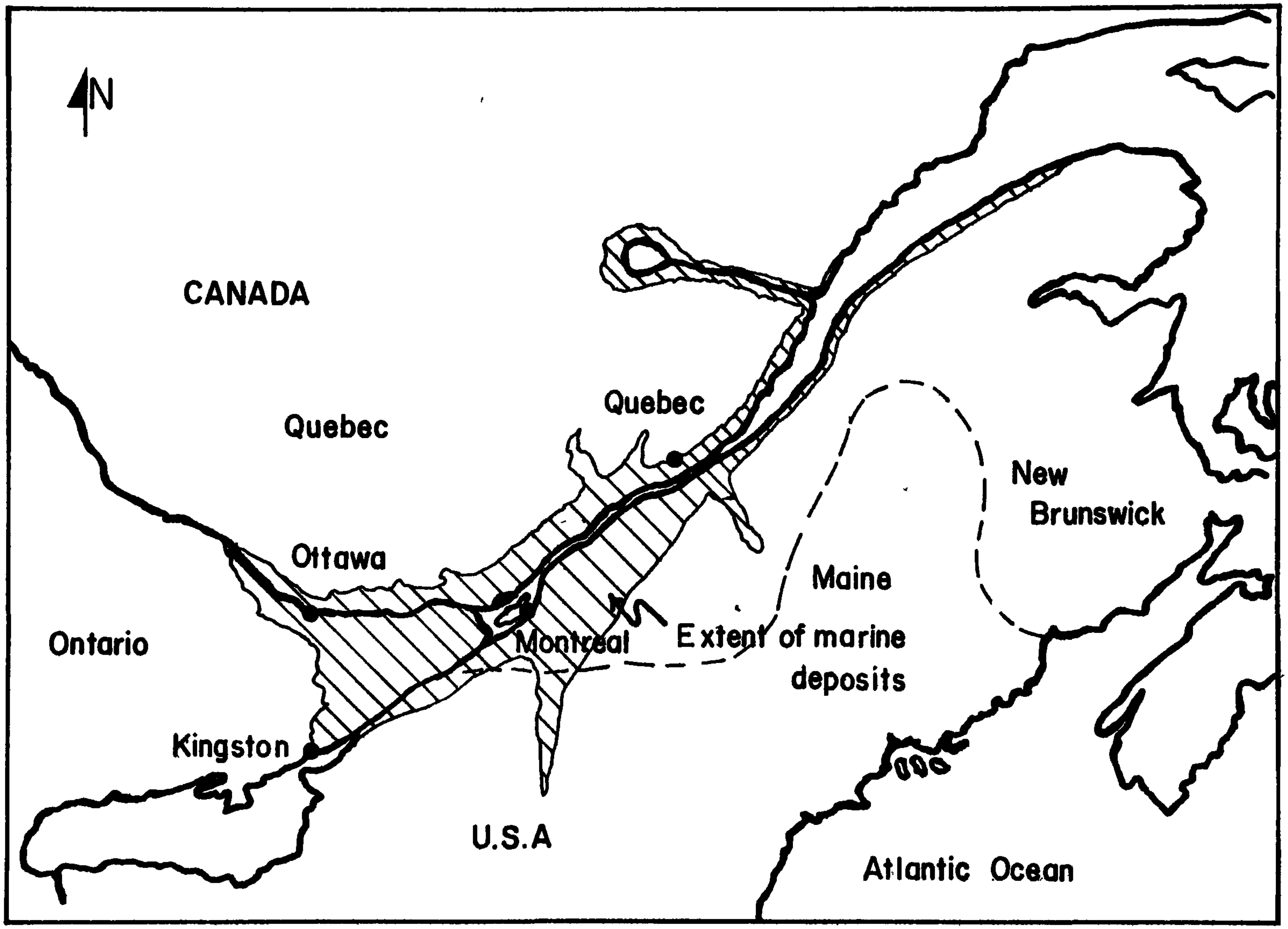


Figure 2.1 EASTERN CANADA AND THE CHAMPLAIN SEA

da clay" in the literature. The christening of the clay is attributed to an early Canadian geologist, Dr. J.W. Dawson (Logan, 1863) and was so named because of the characteristic fossil shells which the clay contains. Gadd (1960) questioned the appellation "Leda" and Larochelle et al (1970) have suggested that the name Champlain Sea clay is more descriptively appropriate than the misnomer Leda. Since the term Leda clay seems to have had wide acceptance in the past, and since "Champlain Sea clay" seems to be gaining wider acceptance, both names will be used to describe the silty clay material deposited by the most recent marine trangression of the Ottawa - St.Lawrence Lowlands.

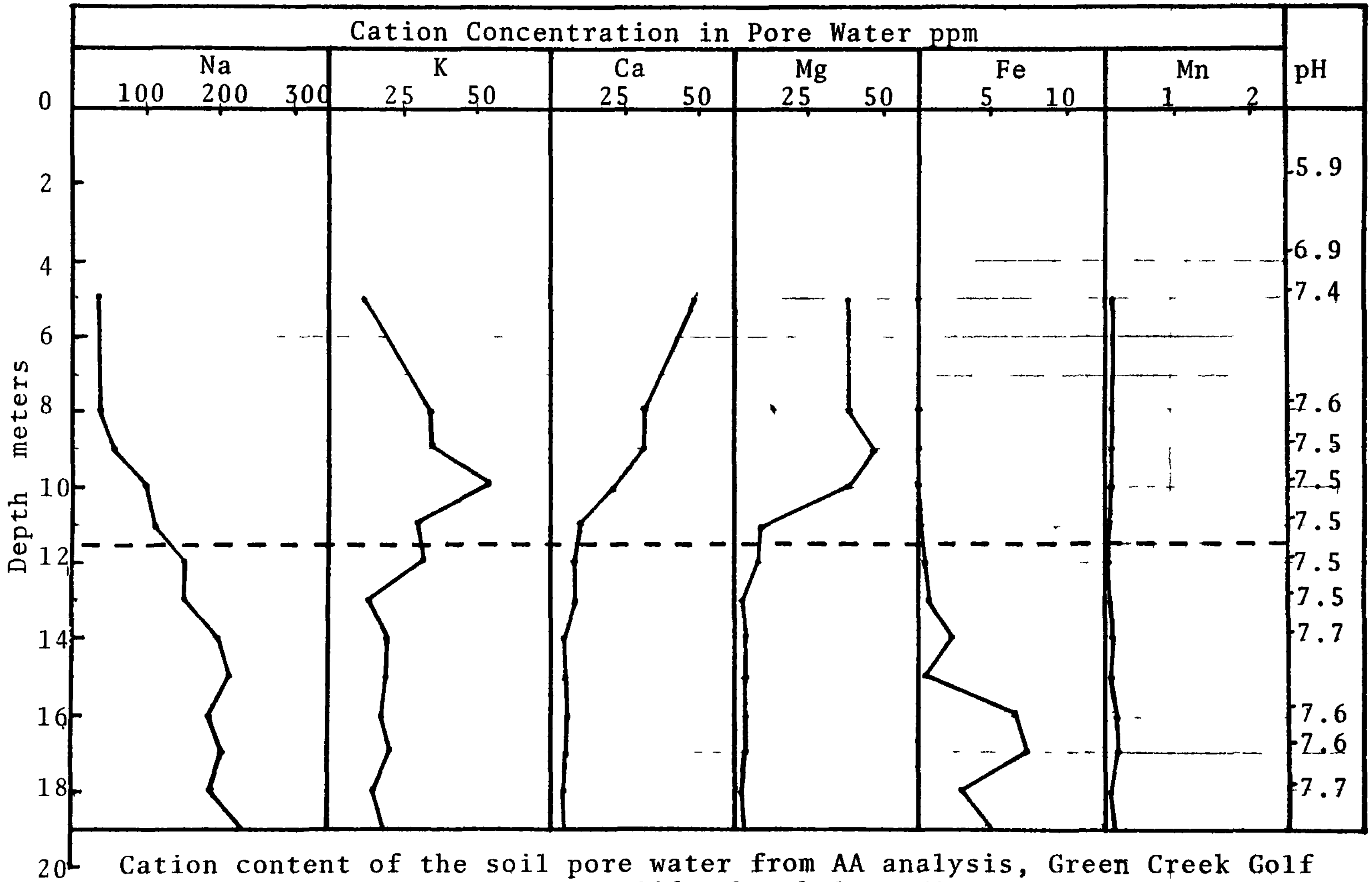
2.3 Geology of the Champlain Sea clay

Although the unusual geotechnical properties of Leda clay have been relatively well investigated because of the engineering problems encountered in this soil, only limited information is available to date on its mineralogy and chemistry. Geological and geotechnical indications suggest that there are two distinct superimposed clay deposits: and "upper"fissured deposit which overlays a "lower" intact clay. The latter is exposed farther east in the St.Lawrence Valley and in zones of greater erosion notably north of the Ottawa river at the foot of the Eardley Escarpment, and at the bottom of Green Creek.

These two clays can be differentiated by crumbling samples: the "upper" fissured clay breaks down to a network of small nodules, less than one centimeter in diameter, while the more plastic and less fissured "lower" clay does not. The "upper" portion of the clay deposit in the Ottawa area usually exhibits rythmic banding of grey to brownish grey layers alternating with pinkish-red horizons. Mineralogical and chemical determinations indicate that this layering probably reflects variations in the conditions of deposition and not irregularities in the source material (P. Gélinas, personnal communication). The "lower" clay is grey-blue in colour and shows black organic mottling (anearobic bacteria); this mottling disappears on exposure to air and is absent in areas of high salt concentrations.

The mineralogy and grain size distribution of Leda Clay in complex and seems to reflect the source material. Primary rock-forming minerals, chiefly alkali-feldspar, plagioclase and quartz with some ferro-magnesian silicates, make up both the sand and silt fractions. The clay size fraction contains a considerable proportion of the above mentioned minerals with abundant illite, hydrous mica, mica and commonly chlorite and vermiculite; expanding clays, such as montmorillonite, are either absent or present in only small amounts (Gillot, 1971). The relative uniformity of soil mineralogy with depth seems to indicate a fairly uniform source of material from site to site; the presence in the finer fractions of rock-forming minerals of low resistance to chemical alteration tends to indicate that these soils experienced little or no weathering. Since the clay fraction is mostly made up of primary minerals and of relatively inactive sheet silicates of small specific surface, the soil should have relatively weak colloïdal properties (Gillot, 1971). Porewater cation determinations (Sangrey and Paul, 1971) indicate an enrichment in potassium, calcium and magnesium of the "upper" fissured soil relative to the high sodium, iron and maganese content of the "lower" clay (see Figure 2.2).

Grain size determinations of Champlain Sea clays from different sites in the Ottawa area show a fairly fine textured uniform distribution in the upper portion of the clay deposits, while this distribution is more variable and less clayey at depth. Chemical and mineralogical determinations indicate a higher total carbonate content in the upper zone material whose clay fraction contains more phyllosilicates with a consequent dilution of rock-forming minerals. Furthermore, the sand fraction of these soils, noticeably in the upper zone, contains pellets of fine silt sized particles which are resistant to dispersion techniques (Brydon and Patry, 1961).



Cation content of the soil pore water from AA analysis, Green Creek Golf Course slide, borehole GCGC1 (Sangrey and Paul, 1971).

Figure 2.2 PORE WATER CATION CONCENTRATION

In an attempt to explain the extent and dual nature of the clay sediments, it has been suggested (Gadd, 1962) that a fresh water inflow, presumably from the Great Lakes region, could have caused a sharp decrease of the salinity of the Champlain sea waters; the change in currents caused by the new inflow would have been accompanied by erosion and redeposition of the original intact clay in a more fresh-water environment, thus creating the fissured clay layer observed in the western part of the St-Lawrence valley. More recently it has been demonstrated (Richard, 1975b) that a "late Newington ice lobe" (circa B.P. 11,200) advanced in the marine waters of the Champlain Sea and incorporated molluscs shells in glacial sediments. This advance, close to 2,000 years after the start of the marine invasion in Ottawa Valley, deformed and overode fossiliferous marine sediments and probably only occupied certain areas of the Ottawa - St.Lawrence Lowlands. Pertubation of normal currents by these north - north-west ice tongue advances, as well as the relative salinity fluctuations caused by glacial outwash and marine reinvasion, could account for the upper fissured clay.

2.4 The Structure of Leda Clay

The Champlain Sea clays show unusual geotechnical properties which may possibly be explained by structural considerations. The structure of a fine grained soil depends on its mineralogy as well as its environment of deposition and geological history. Many flow type slope failures have occurred in certain areas of the Ottawa - St.Lawrence Lowlands, and the material is defined as an highly sensitive "quick clay".

The high sensitivity to remolding of the Leda clay, as illustrated by Crawford (1968), can be explained by the available electrolytes in the sedimentation environment. Since these soils settled out in brackish waters, the high electrolyte concentration would cause inter-particle attraction and floculation of the clay particles. This random oriented coagulation of the clay sized plate shaped mineral grains (Cabrera and Smalley, 1973) would result in a card-house type structure; the soil would thus have the observed high porosity and water content, and any remolding of the sediment would cause a breaking of the weaker bonds and a structure collapse followed by a rearrangement of the particles from a near fluid state (Laventure and Warkentin, 1965).

This randomly floculated structure has been observed in electron-photomicrographs of undisturbed samples of Leda clay (Crawford, 1968). Fabric reorientation due to overconsolidation, using X-ray diffraction (Quigley and Thompson, 1966) and electron microscopy (Crawford, 1968), and along micro-fissures, using optical methods (Jarret, 1972), has been demonstrated. Permeability determinations of oriented samples (Laffont (1977) indicate horizontal to vertical permeability ratios in the order of 2:1 to 5:1, which would correspond to the low anisatropy expected from a structure built of randomly oriented particles.

Due to the non-clay nature of these soils, only particle cementation could account for the cohesive character exhibited. Quigley (1968) proposes precipitates of aluminun and iron hydroxides as the bonding agents, and Townsend (1965) observes that calcium carbonate is common in Leda clay. Gillot (1969) remarks that the effect of clay minerals should not be entirely dismissed since these soils do show irreversible structure collapse and cohesion upon drying.

Moon (1973) reports, for shearing rate tests done on aqueous solutions of clay-sized quartz particles, that this artificial clay exhibits weaker shearing resistance at low strain rates than for abrupt failures. This observation corresponds to those made on Champlain Sea clay and would tend to support the progressive type mode of failure proposed for Leda clay. This suggests the use, in slope stability analysis, of the soil's residual shear strength. The weaker strength at low strain rates can explain the small straining to failure observed in these cemented soils (Sangrey, 1972b).

Figure 2.3 shows the dispersion potential for the upper and lower clays determined by the method described by Sherard et al (1972) from the data in Figure 2.2. The high sensitivity of the lower intact clay seems related to the ratio of sodium to total dissolved cations, though the correlatable data is insufficient for the present method to be conclusive.

Sangrey (1972b) proposes that, since glacial mechanical weathering results in the rock flour which makes up Champlain Sea clays, and since this environment is not chemically very active, the primary rock forming minerals have not been exposed long enough to be completely altered to clay minerals. He however speculates that alteration is actually taking place and that secondary sheet silicates are being formed. He notes that ferromagnesian minerals, particularly hornblende, readily weather to form chlorite, vermiculite and hydrous oxides of iron, aluminum and manganese (Loughnan, 1969). The amphibole-chlorite-vermiculite mixture is very common in Leda clay, especially in the finer textured upper zone, and the oxides presumably formed by the above weathering reaction would be the precise material needed to form cementing gels. Since the above mineralogical reaction results in a net volume decrease of the soil particles involved, this in situ weathering could possibly account for the fissuring of the upper clay deposit.

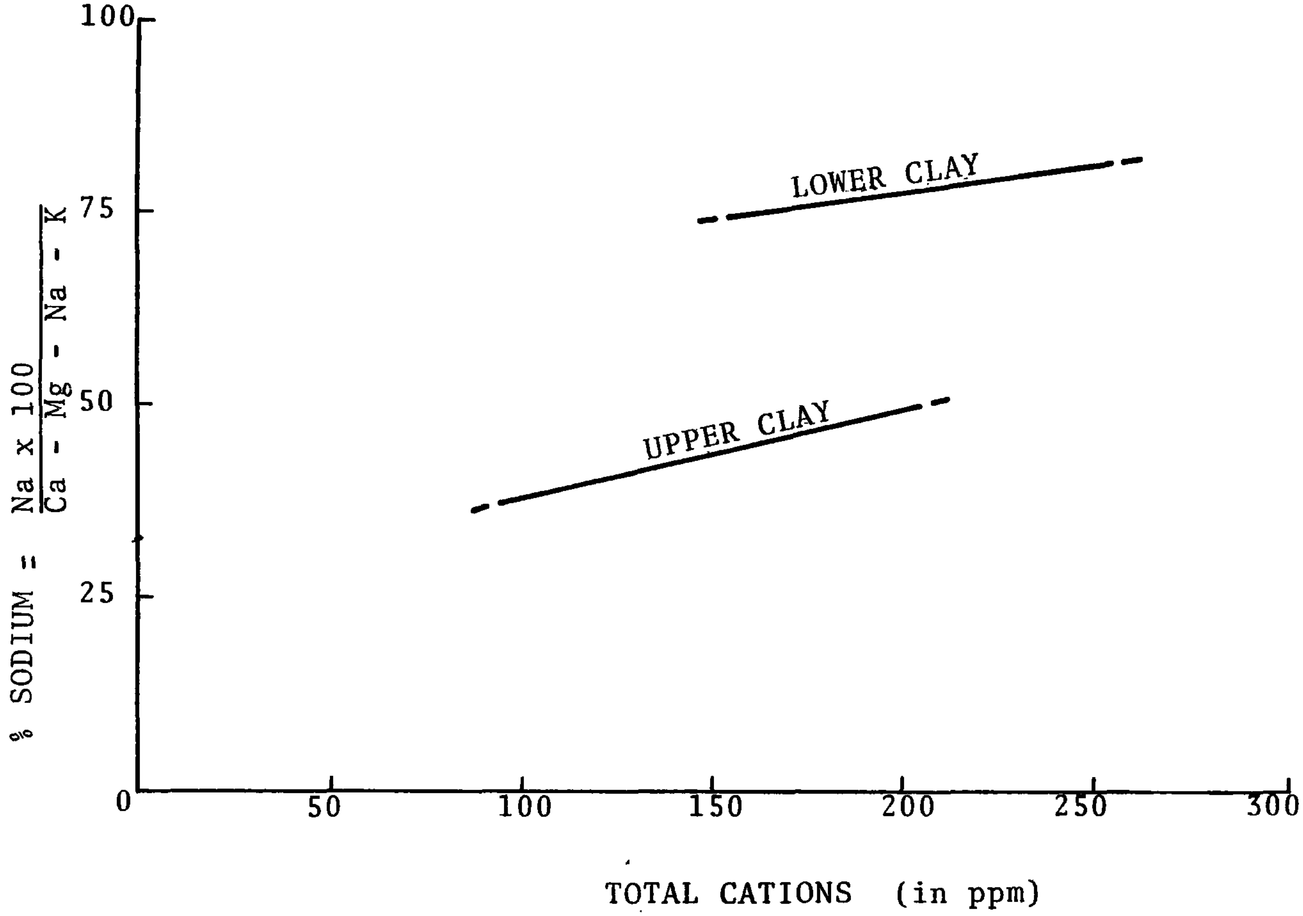
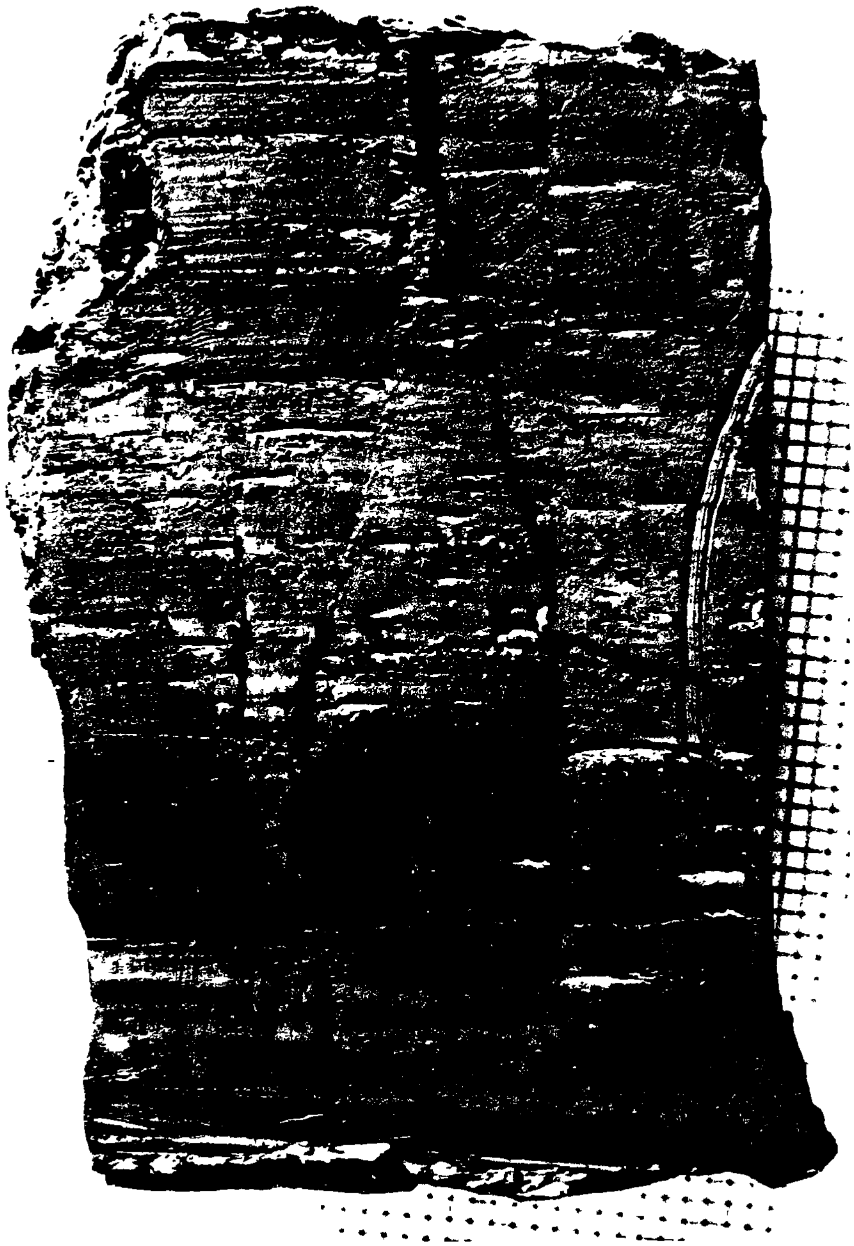


Figure 2.3 SODIUM vs TOTAL DISSOLVED CATIONS

This proposal of the mode of formation of the upper fissured clay deposit through weathering and micro fissuring seems to be, to date, the most comprehensive theory as it takes into account both the overconsolidation of the soil as well as its strongly fissured nature compared to the mineralogically similar but less-fissured lower deposit; the weathering mechanism invoked appears to agree with that proposed by Eden (1975) who seems to relate the upper clay zone to a weathered crust. Figure 2.4 is a photomacrograph of the fissure system reported by Jarret (1972) and Toombs (1973) and observed by the writer in many samples of the upper Leda clay zone. These fissures are usually inclined from 60 to 70 degrees and can presumably indicate the downward displacement of soil units due to shrinkage of the soil mass. The weathering theory can also explain the variation in elevation of the intact-fissured clay interface, as well as the irregular distribution of strength properties from site to site.

2.5 Geotechnical Properties of the "Upper" and "Lower" Clays

The engineering properties of Leda clay have been well investigated by many researchers. Crawford (1968) presented a state of the art paper on the geotechnical properties of the Champlain Sea clay in the Ottawa area. The main characteristics of the soil properties are indicated in Figure 2.5.



Fissures and silts bands in a photomacrograph.
Scale approximately 1.25:1

Figure 2.4 FISSURES IN LEDA CLAY

	Location	Surface elev., ft	Depth, ft	p'	S_u	p_n	S_u/p_n	S_t	SC	Averages w, %	Averages I_P %	Averages I_L	Averages -2μ, %	Averages γ, lb/cu.ft.	Std. error, kg/sq.cm. p_n	Std. error, kg/sq.cm. S_u	Remarks
A	Brecken-ridge	330	20	67	36	1 2	30	20–	0.4–	79	38	1 4	80	96	± 21	± 07	Uniform clay, low carbonates. Drying crust extends to 20 ft. Extensive clay deposit to great depths.
			100	2 14	.91	2 9	.31	150	3.4								
B	Sewage plant	171	20	38	1 00	3 0	33	25–	.1–	56	19	2.0	60	105	—	± 15	Highly plastic clay to 50 ft, medium sensitivity. Below 50 ft, somewhat coarser, extremely sensitive.
			70	1 44	1 00	4.1	.25	500+	2.1								
BB	Sewage plant	171	30	56	1 47	4 5	.33								—	—	
			70	1 44	1 87	5.2	.37										
	Green		20	.08	75	3.1	.24	5–	.6–								Medium to highly plastic clay throughout. Salt content increases linearly from 0.6 grams/liter to 13 7 grams/liter. High carbonates at depth - same clay terrace as B.
C	Creek Fill	182	100	2 38	1 98	4.9	.40	25	13.7	66	40	0.9	70	104	± 44	± 20	
	Green		20	60	64	2 0	.32	20–	.1–								Fine clay throughout. Drying crust to 20 ft. Extremely sensitive at greater depths. Higher terrace than B.
D	Creek Slide	277	90	2 02	1 02	3.0	.34	500	.5	69	34	1.7	77	101	± 34	±.12	
E	National Research	310	30	83	.55	1.8	30	15–	.1–	68	20	2 5	60	98	± 37	± 11	Clay throughout becoming siltier with depth. Drying crust extends to 30 ft. Extremely sensitive at depth. Isolated clay valley.
			60	1 10	.77	2 3	.33	500+	1.5								
F	Main St.	222	15	52	.57	2 3	.25	15–	.1–	51	22	1.7	50	112	± 49	± 15	Highly plastic clay at surface becoming siltier with depth. Extremely sensitive at depth. Isolated clay pocket.
			65	1 74	1 03	3 9	.26	500+	.6								
G	National Museum	235	20	.86		1 6		10–	.1–	68	40	2.2	56	105	—	—	Same as for F.
			50	1 45		2 4		150	1 8								
H	Heron Rd.	250	20	70	58			20–	3–	40	14	2.4	51	108	—	± 14	Highly plastic clay becoming siltier and extremely sensitive with depth.
			90	2 20	.75			70	.5								
I	Gloucester	260	10	16	21	0.6	35	30–	.5–	72	23	2 0	71	99	± 15	± 06	Fine clay throughout. High water content, low plasticity, high sensitivity. Carbonates high. Extensive level clay plain. Drying crust to about 10 ft.
			60	.96	.56	1 7	33	500+	2.1								
J	Kars	280	20	38	29	1.2	24	25–	.2–	60	20	2 0	60	101	± 22	± 07	Extremely sensitive clay layer from 20 to 50 ft. Alluvium and drying crust to 20 ft.
			50	.95	.52	2 0	.26	500+	.7								
K	Walkley Rd.	255	15		.50										—	±.07	
			45		.70												Highly plastic clay - bedrock less than 50 ft.
KK	Walkley Rd.	255	33		.62	2 2	28	50	1.7	58	28		62				

p' = effective overburden stress, kg/sq.cm.; S_u = undrained shear strength, kg/sq.cm.; p_n = preconsolidation pressure, kg/sq.cm.; SC = salt content grams/liter.

Figure 2.5 SUMMARY OF SOIL PROPERTIES OTTAWA LEDA CLAY (from Crawford and Eden, 1965).

Sangrey and Paul (1971), in a study of the clay horizons at Green Creek, established the index properties differences between the upper and lower clay deposits (Figure 2.6). Generally, both clay types seem to show approximately the same water content. The higher plasticity of the fissured soil reflects its higher clay material content (Bjerrum, 1954); the liquidity index of the intact clay is thus superior to that of the upper material, though the strength is fairly uniform from one clay to the other. The intact clay shows a very high sensitivity due to a comparatively weak remolded shear strength.

Figure 2.7 shows the types of effective shear strength envelopes normally demonstrated by each of the two clay soils. Both these envelopes show a strong curvature in the low normal stress range, and the intact clay behaves as a cohesive material under very low normal stresses. This apparent cohesion seems to be absent in the upper clay probably because of its intense small scale fissuring.

The shear strength envelope will be discussed in greater detail in Chapter 3.

Most of the Leda Clay deposits are capped by a stiff highly weathered crust that demonstrates a greater shear resistance than the underlying clayey material. Eden (1975) seems to incorporate in the crust zone all the wea-

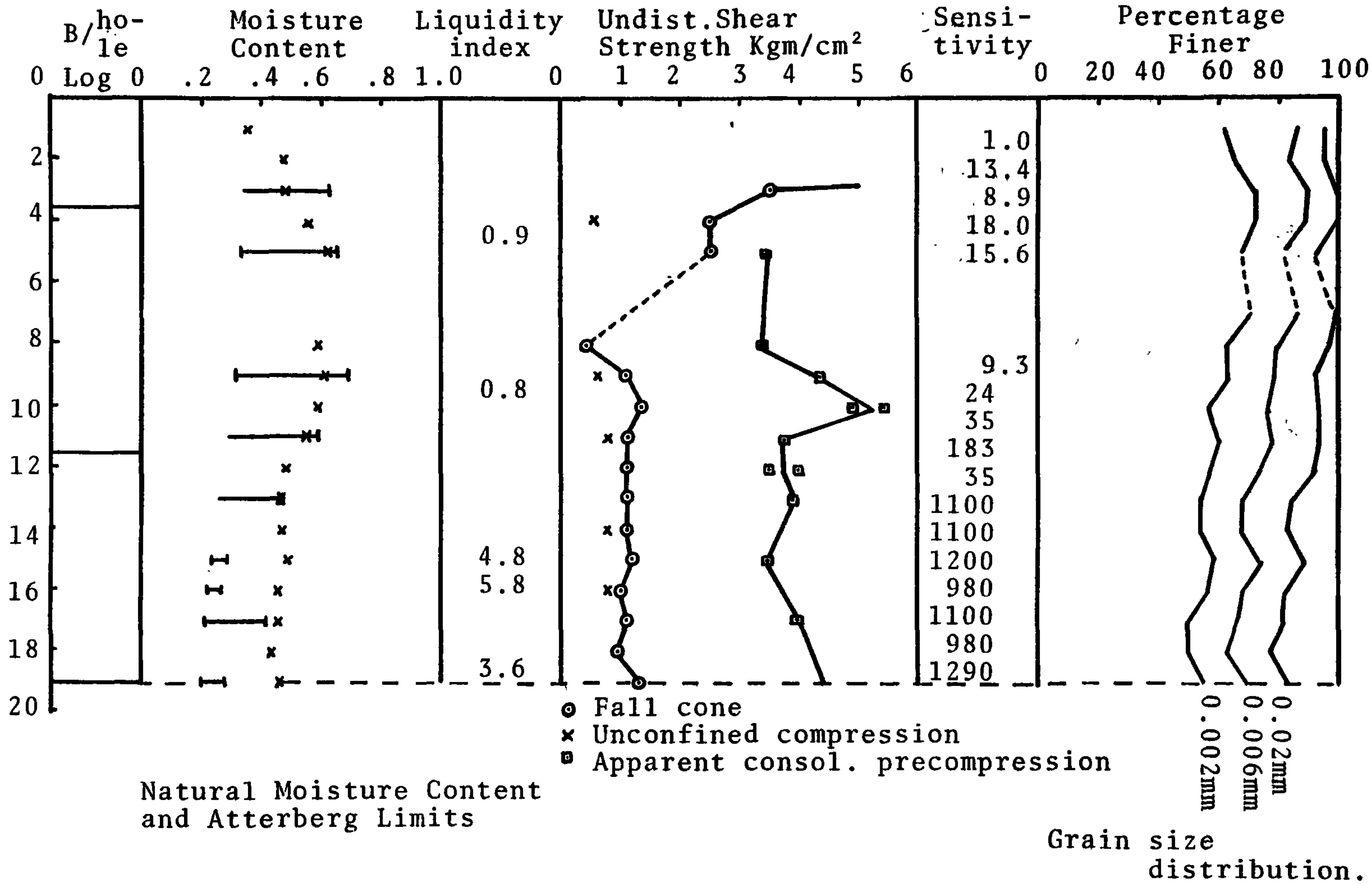
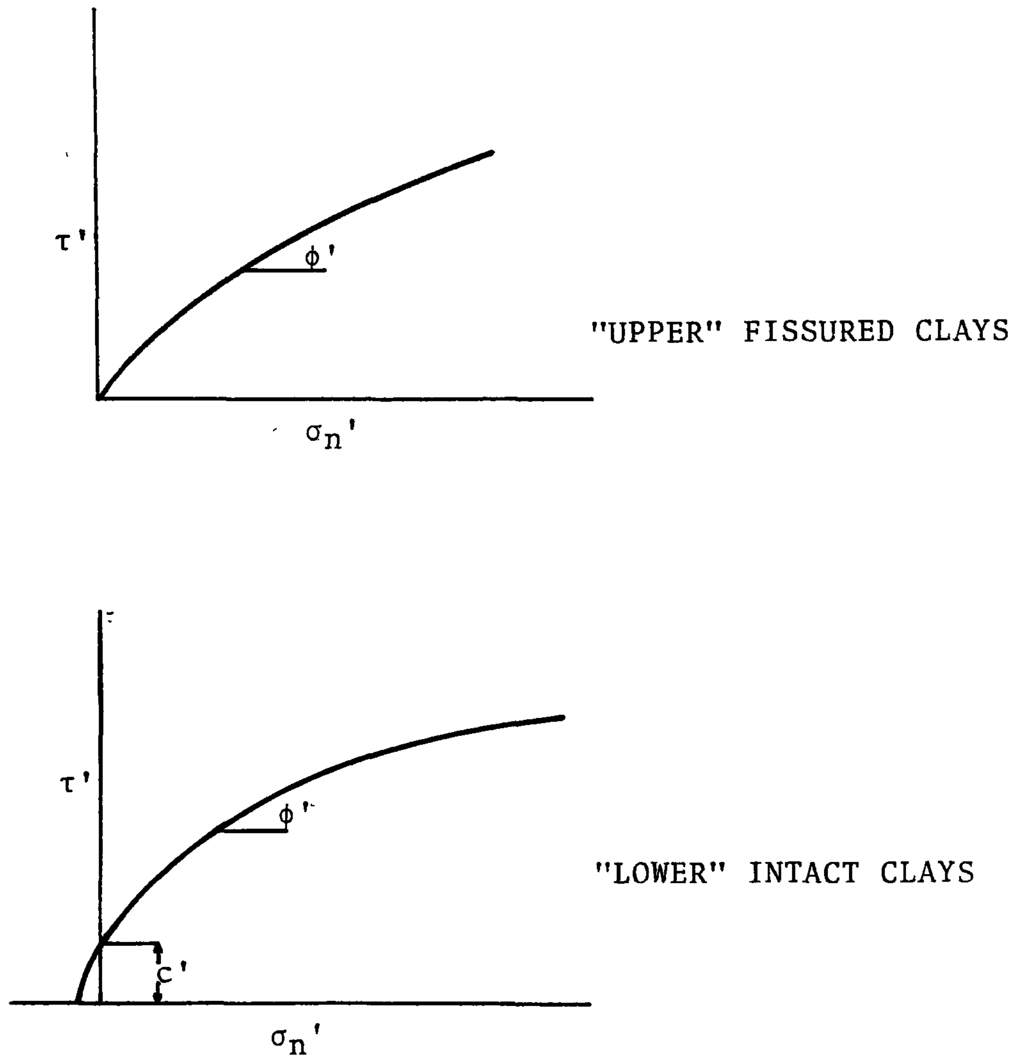


Figure 2.6 ENGINEERING INDEX PROPERTIES FOR THE SOIL PROFILE AT GREEN CREEK GOLF COURSE SLIDE. (from Sangrey and Paul, 1971)



σ' = effective normal stress

τ' = effective shear strength

Figure 2.7 REPRESENTATIVE SHEAR STRENGTH ENVELOPES FOR UPPER AND LOWER CLAYS thered material, including the upper fissured clay horizon, which could presumably be considered undergoing chemical alteration (Sangrey, 1975b). In this system of definition, "this crust is identified by a decrease in undrained strength with depth to a minimum value as measured by the field vane then an increase with depth thereafter." The point of minimum strength marks the extent of the weathered crust. "The weathered crust is further characterised by a system of closely spaced fissures" and commonly extends "to depths of 30 feet or more". "The initial stages of landslides in the clay slopes are confined to the crust". (Eden, 1975).

For most researchers reporting in the literature in the past, the accepted meaning of "crust" referred to the strongly desiccated zone above the inferior limit of the groundwater fluctuation zone. The crust thickness is variable and can be very thin, especially on slopes where the erosion rate is equal to the rate of crustal formation. Eden and Mitchell (1973) indicate that in most cases the depth on initial failure is "below the depth of active weathering".

Since the strength of the desiccated zone influences the stability of Leda Clay slopes, it is most likely that any rupture plane will preferably develop in the weathered substratum where most of the shear strength is provided by the soil below the ground-water fluctuation zone.

CHAPTER 3

THE STRESS-STRENGTH RELATIONSHIP AND THE BISHOP METHOD OF ANALYSIS

3.1 General

Studies of the shear behaviour of the fissured Champlain Sea clay from the Ottawa area indicate that the normal stress-shear strength relationship for these soils cannot be properly represented by the classical Mohr-Coulomb failure envelope. This envelope, normally defined as a straight line, is irregularly curved for the tested soils.

Following is a discussion of the Mohr-Coulomb envelope and of the shear strength characteristics of the fissured Leda Clay. A method for evaluating shear strength from the normal stress dependant parameters obtained by the representation of the soil's failure envelope using a series of straight lines is suggested. The Bishop modified equation is revised to used this stress dependant shear strength parameter.

3.2 The Classical Mohr-Coulomb Envelope

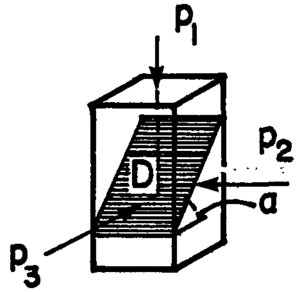
The stresses applied to a soil, as in a triaxial testing apparatus, can be represented by a circle of stress corresponding to a limiting combination of normal and shear stresses (Figure 3.1). If a series of these stress combinations are applied to a same material type, the upper limit of the group of stress circles thus obtained describes the stress-strength relationship of this material, for the observed conditions under which rupture will occur (Figure 3.2). The upper limit of an indefinite number of these stress circles is defined by the tangent to these circles and is known as the Mohr-Coulomb failure envelope.

Since the curvature of the failure envelope is usually negligible for an homogeneous and isotropic soil, it is assumed that this stress to strength relationship may be approximated by a straight line of the form

$$\tau = c + \sigma_n \cdot \tan\phi$$

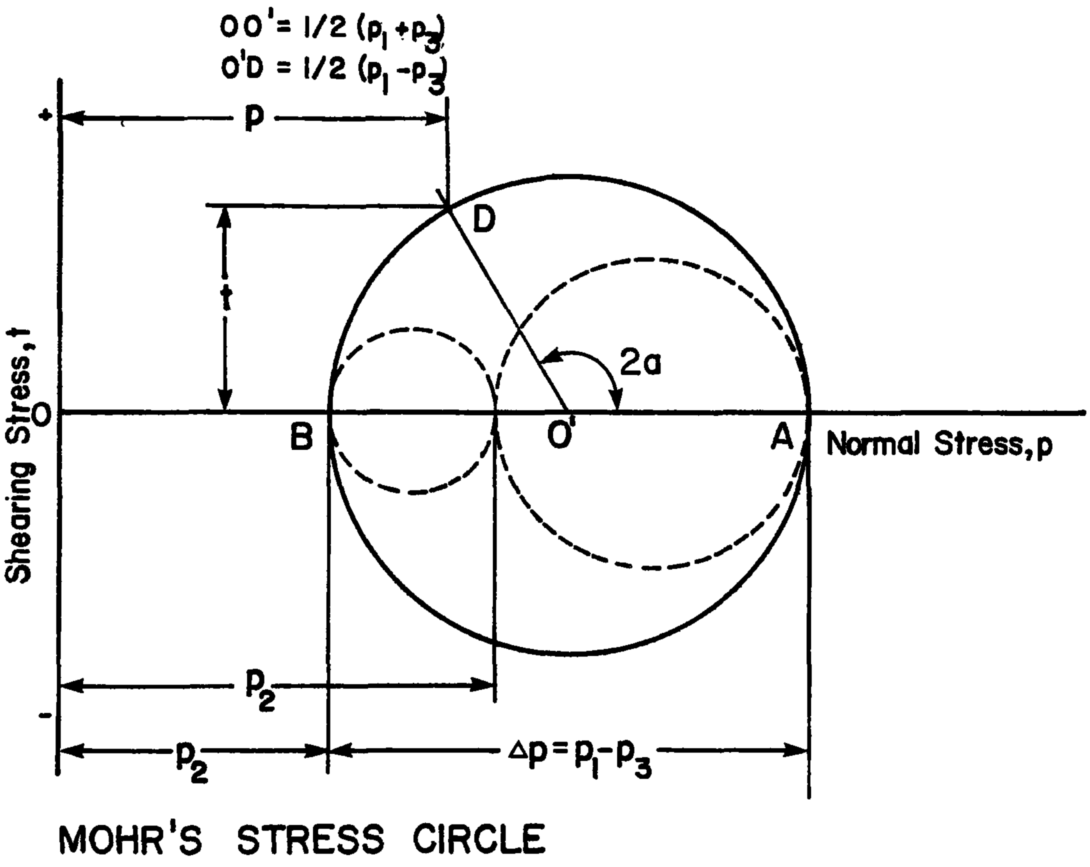
where τ is the shear strength (abscissa),
c is the cohesion or τ- intercept,
σn is the normal stress (ordinate) and
$\tan\phi$ is the slope of the straight line.

This expression is called Coulomb's equation.



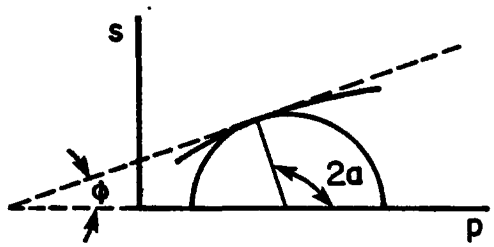
(a)

PRINCIPAL STRESSES
ACTING ON AN
UNIT BLOC OF SOIL



MOHR'S STRESS CIRCLE

Figure 3.1



FAILURE ENVELOPE FOR A SERIES OF FAILURE CIRCLES

MOHR-COULOMB FAILURE ENVELOPE

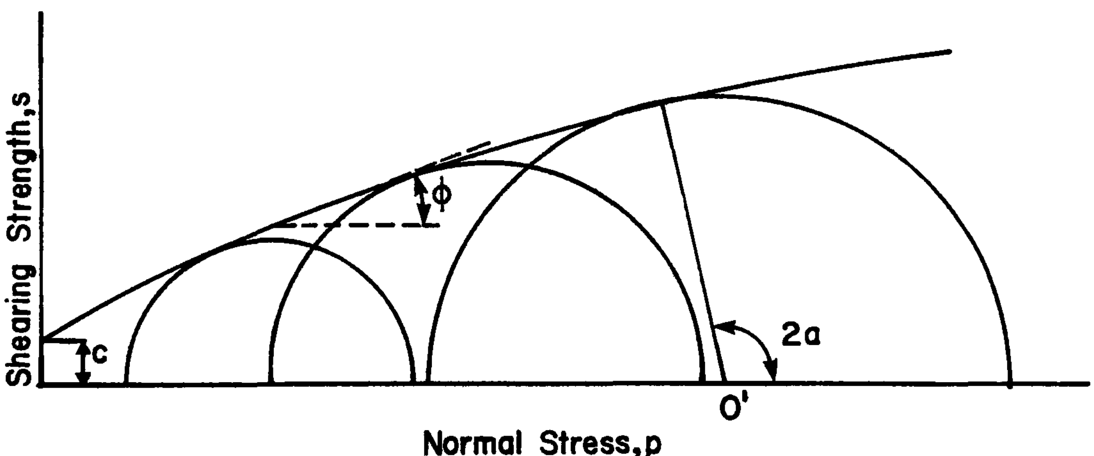


Figure 3.2

The above relationship is only valid for isotropic dry soils. In saturated conditions, part of the normal stress is hydrostatically carried by the pore fluids which have a null shear resistance. The "revised" Coulomb's equation for saturated soils is then, in terms of effective components,

$$\tau' = c' - \sigma_n' \cdot \tan\phi'$$

where $\sigma_n' = \sigma_n - u$ and

u is the pore pressure acting on the precise area under consideration.

From the approximation of the failure envelope by a straight line, the effective strength properties of a natural material in classical geotechnical engineering are generally defined by a fixed effective cohesion, c', and a constant effective angle of internal friction, ϕ'. These "parameters" are not soil properties in themselves, but constants defining the geometrical straight line model which is assumed to describe the soil's behaviour.

Though this straight line model may be valid for most soils, it is presently thought by many researchers to be non-representative of the shear behaviour of the Champlain Sea clays in Eastern Ontario and Western Québec.

3.3 The Fissured Leda Clay Stress-Strength Envelope

Reports of quantitative determinations of the behaviour in shear of the Ottawa clay seem to indicate a three part comportment. Figure 3.3 shows an idealized failure envelope for the fissured Champlain Sea clay compiled from data published by Crawford and Eden (1967) and Mitchell (1970b). The stress level dependency of the soil's shear strength is demonstrated by the curvature of this envelope. A low stress range envelope linearly extrapolated from the high stress range data is also indicated on this figure.

In a comparison of laboratory testing procedures and actual in situ conditions, Crawford and Eden (1967) indicated the inadequacy of extrapolating the high stress range envelope to lower stresses (Figure 3.3) for slope stability analysis, due to the difference in behaviour of the clay above and below preconsolidation pressures. Their investigation of the stress range below preconsolidation gave a horizontal envelope, and Townsend et al (1969) proposed that this soil has an essentially cohesive behaviour at stresses below the preconsolidation pressure.

Further testing by Mitchell (1970b) demonstrated that the shear strength components of the fissured Leda clay vary considerably in the low stress range with the applied effective normal stress, from essentially frictional under very low stresses to essentially cohesive at higher stresses below the preconsolidation pressure.

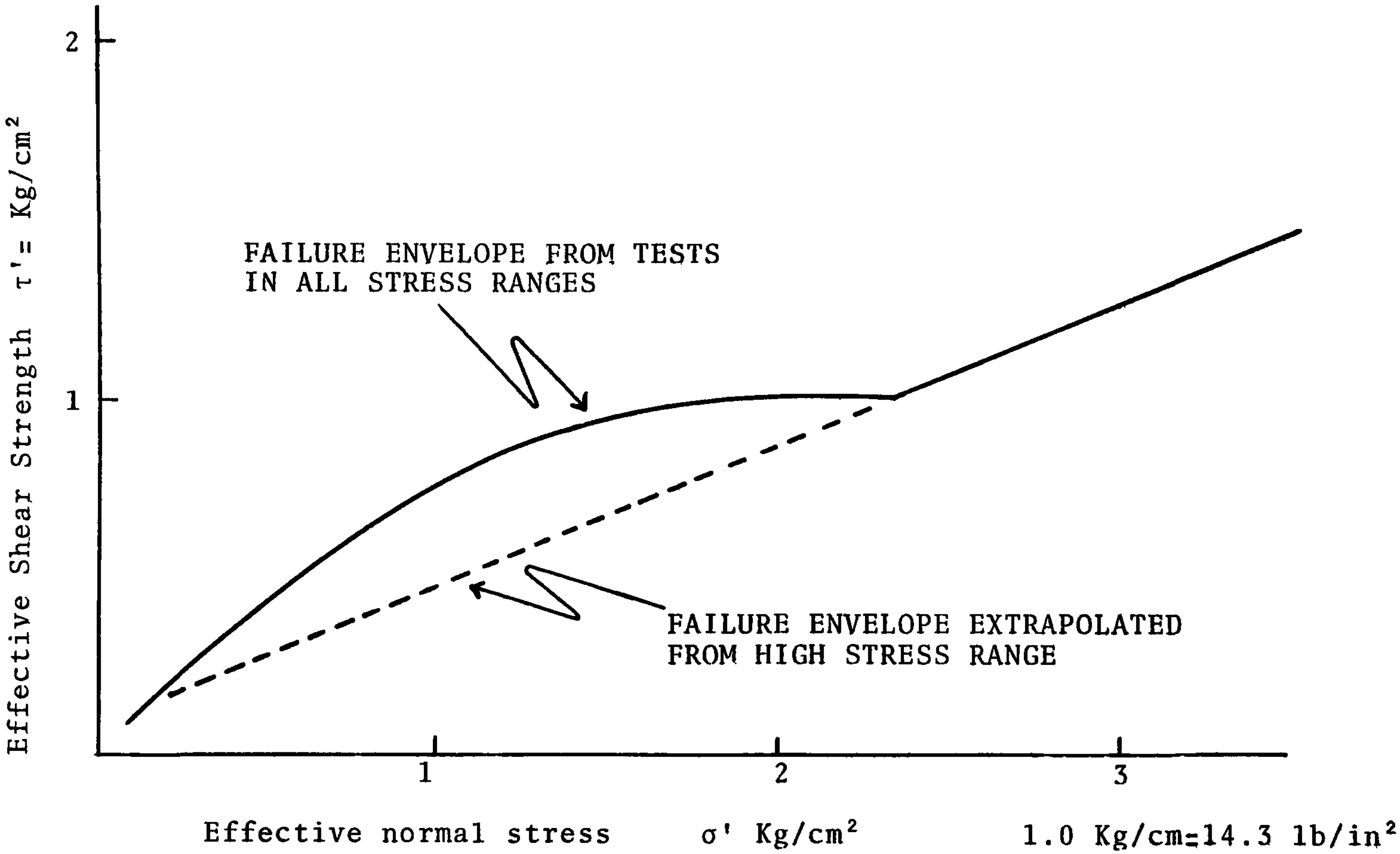


Figure 3.3 IDEALIZED FAILURE ENVELOPE FOR FISSURED LEDA CLAY

Tension tests of these fissured soils (Jarrett, 1970) indicated no noticeable tensile strength for nine out of ten samples tested, while the "lower" less fissured clay showed cohesion to varying degrees as indicated by the τ'-intercept (Lo and Morin, 1972).

Figure 3.4 is a schematic representation of the Ottawa fissured clay failure envelope on which the three different stress ranges, high, intermediate and low, are indicated.

In the high stress range, above the measured pre-consolidation pressure, the slope of the failure envelope exhibits the essentially frictional nature of the mechanical strength of the clay, the shear strength being directly proportional to the applied normal stress. A rupture at these high stresses is usually accompanied with a large volume decrease; there is a general deformation of the material with no definite failure surface developed. This portion of the fissured clay behaviour is attributed to a complete breakdown of the clay structure and has been termed "work hardening plastic flow" by Eden, (1975).

The nearly horizontal component of the shear strength envelope in the intermediate stress region implies mainly cohesive properties with only minor frictional characteristics, if any. The shear strength is fairly constant through-out and

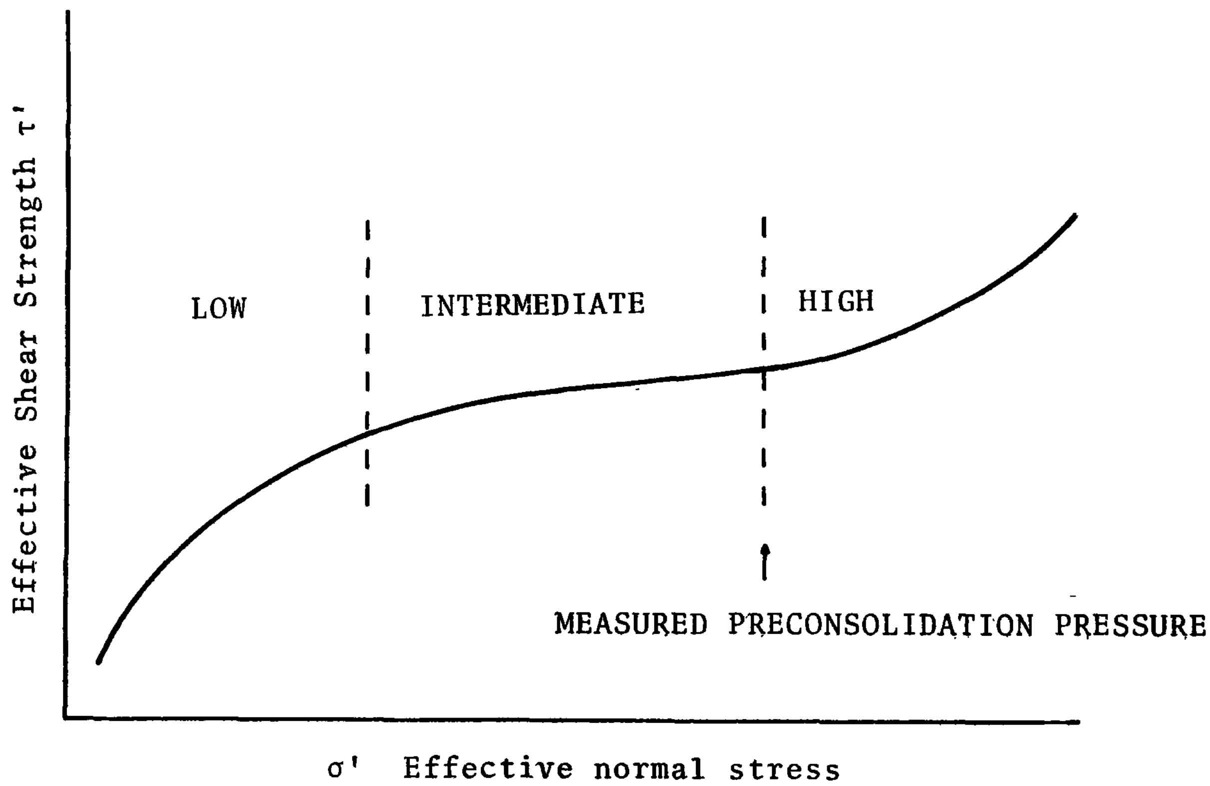


Figure 3.4 SCHEMATIC EFFECTIVE NORMAL STRESS vs SHEAR STRENGTH ENVELOPE FOR FISSURED LEDA CLAY

failure occurs along well defined planes with little or no volume change. The brittle nature of the mechanical resistance in this region probably implies shearing of the bonds between particles. Anisotropy has its greatest effect on shear strength in this range (Mitchell, 1970).

The slope of the envelope in the low stress range indicates a high frictional shear strength component with little or no cohesive part. Strain under low stresses is usually related to volume increase, and the material seems to behave like a dense granular soil and exhibits dilatancy. At failure, the clay breaks down to a fluid mass of small nodules along the failure plane. This behaviour is presumably caused by the weak confining stresses which permit a relative displacement of the "flocs" without rupture of these basic units. This low stress behaviour is considered important for slope stability analysis since initial failures usually occur in the upper portions of the soil mass, just below the desiccated crust, when an abundant "supply of free water is available" (Eden, 1975). Furthermore, the state of the debris after a slope failure is similar to the condition of the low stressed soil at rupture (Jarret, 1972).

It would appear, from the above observations, that the fissured clay envelope shows little or no cohesive properties in the very low stress range though its exact behaviour is unknown and is probably related to the nature of the micro-fissures on the weakest planes. Extrapolating the low stress envelope from the high stress region normally gives more conservative shear strengths than actually measured. In slope stability analysis, the high stress shear strength envelope is of little practical importance since the loading of a slope above preconsolidation pressure would in all probality result in failure before the overcharging is completed The behaviour of soil slopes in shear is primarly concerned with intermediate and, predominantly, low stresses; it is of the utmost importance to establish precisely the clay's behaviour in the $\sigma n' = 0$ and slightly above stress region, since a small cohesion may have considerable influence on the calculated factor of safety.

3.4 Manipulation of the Curved Envelope

Stability analyses normally rely on a fixed cohesion and internal friction angle to describe the soil's shear strength. Since most of these investigations in the Ottawa area are mainly concerned with the low stress range, as illustrated by the observed shallow failure surfaces on actual slides, this part of the curved failure envelope of the fissured Leda clay is usually approximated by a single straight line whose Y-intercept and slope presumably define the soil's shear strength parameters (Eden, 1975).

Toombs (1973) suggests that the curved failure envelope could be represented by three straight lines each defining the low, intermediate and high stress ranges. This solution, though giving a better picture on the soil's overall behaviour, does not permit a more precise manipulation of the curved stress-strength envelope in the low to very low stress region since this part of the Mohr-Coulomb failure envelope is again approximated be a single straight line as in the previously described technique.

Since most slope stability analyses are done today using computer methods, the curved failure envelope could be better represented by the use of a high degree polynomial of the form

$$\tau' = a \cdot \sigma'^5 + b \cdot \sigma'^4 + c \cdot \sigma'^3 + d \cdot \sigma'^2 + e \cdot \sigma' + f$$

where the constant a, b, c, d, e and f can be obtained by a curve fitting method as similarly suggested by Lo and Lee (1973).

The curved failure envelope can also be represented by a series of straight lines each having a definite $\sigma n'$ range as indicated on Figure 3.5. The method of approximating the curved failure envelope by a series of straight lines is thought to have better practical applications since it requires no particular fitting method and gives a direct representation of the τ'-σ_n' relationship. In each of the two latter cases, the effective shear strength needs not

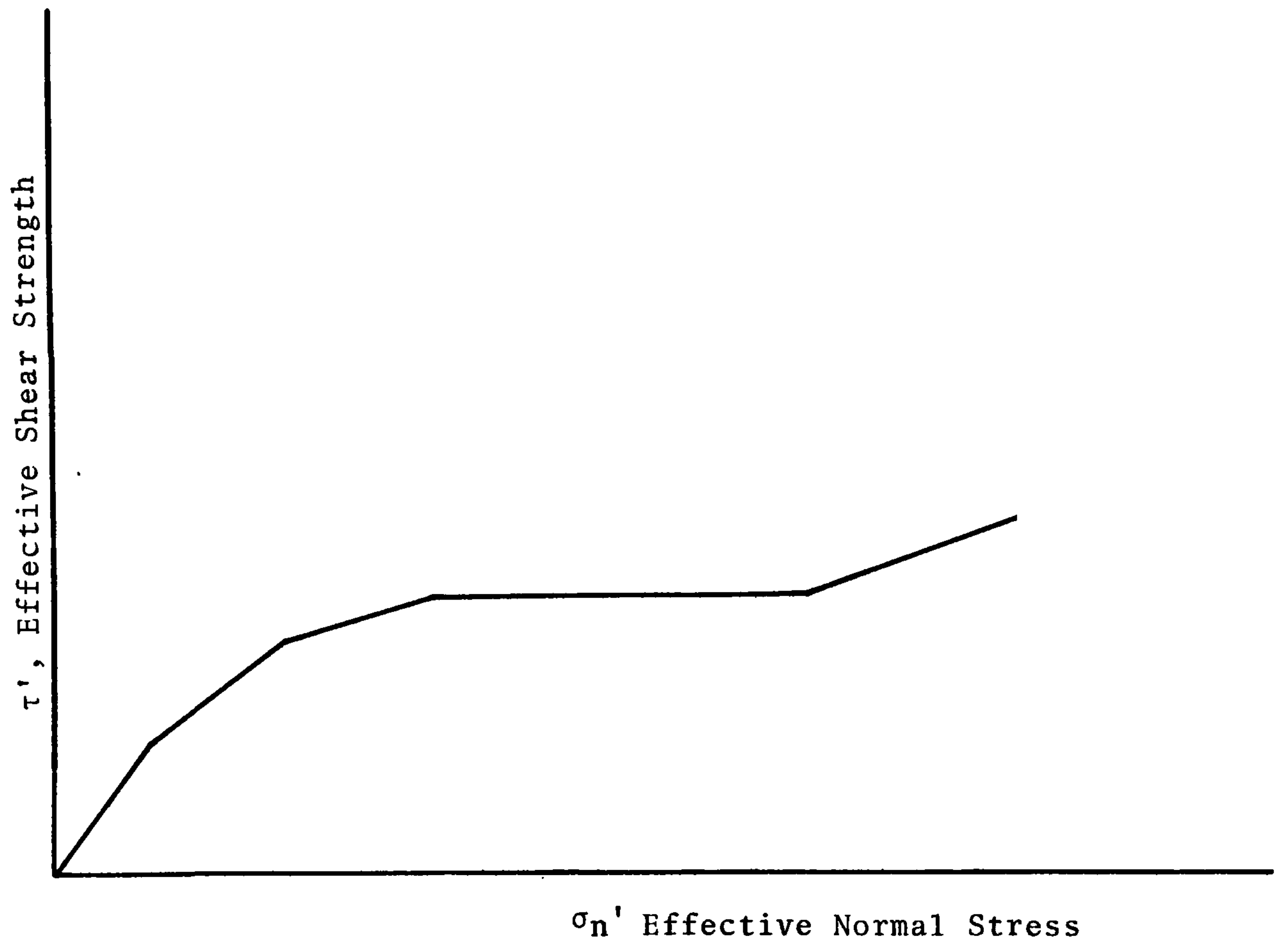


Figure 3.5 CURVED FAILURE ENVELOPE REPRESENTED BY A SERIES OF STRAIGHT LINES

be expressed in terms of cohesion and internal friction angle, but as a function of σ_n', the effective normal stress. The use of an equation of the form

$$\tau' = f(\sigma_n')$$

in slope stability analysis to describe the soil's shear strength behaviour needs only a minor revision of the stability equation used.

3.5 The Applicability of the Bishop Method of Analysis

Various methods for evaluating the stability of slopes have been developed; most of these were originally designed for hand calculations and contain limiting assumptions to allow reasonably fast solutions. With the advent of computers, most of these methods have been programmed and new techniques have also been developed; some comprehensive computer slope stability programs offer a wide spectrum of the available methods and a user is now faced with choosing the analysis method best adapted to the problem at hand.

Whitman and Moore (1963), in a comparative study of the then available slope stability analysis methods, suggest that the friction circle method with a half sine wave normal effective stress distribution to be closer to the "most correct" solution and recommend the use of the Bishop method as the most practical method of solution. Since the observed mode of failure in the Champlain Sea clay slopes of the Ottawa area is similar to the circular arc failure surface assumed by the Bishop method, and since the results obtained from this method seems representative of field observations, the Bishop modified method of analysis is widely accepted by professional investigators and is the method chosen for the present parametric study.

3.6 Review of Bishop's Modified Method of Analysis

The Bishop method of analysis is based on the limit equilibrium of forces and moments, and involves choosing a circular failure surface and dividing the sliding portion into slices. The basic assumptions of the method are:

- the soil behaves as a Mohr-Coulomb material,
- the factor of safety is the same for all slices and
- the sum of the vertical shear forces on each side of the slices is negligible, so that these forces may be considered equal and opposite ($X_n + X_{n+1} = 0$).

The above assumptions have been questioned by some researchers and should be considered as approximations. A more complete evaluation of the forces acting on a general sliding mass is given by the Morgenstern-Price method. The following review of the Bishop expression takes into account the modification of defining the shear strength of a Mohr-Coulomb material as a function of the effective normal stress.

Figure 3.6 is a representation of the slope geometry and of the force diagrams.

If a slope at the verge of sliding is at equilibrium, the sum of the stabilizing moments is equal to the sum of the overturning moments,

$$\Sigma S \cdot R = \Sigma W \cdot x$$

If $x = R \cdot \sin\alpha$

and $S = \dfrac{\tau' \cdot l}{F}$,

$$F = \frac{\Sigma \tau' \cdot l}{\Sigma W \cdot \sin\alpha}$$

The factor of safety is then the sum of resisting moments over the sum of overturning moments.

The effective shear strength, τ', is defined by the Mohr-Coulomb envelope as a function of the effective normal stress

$$\tau' = f(\sigma_n')$$

To find τ' in terms of σ_n', we must resolve σ_n. From the force diagram, the total unit stress acting at the base of a slice is

$$\sigma n = \frac{P}{l} = \frac{P'}{l} + \frac{u \cdot l}{l}$$

$$\sigma_n' = \frac{P'}{l} = \frac{P}{l} - \frac{u \cdot l}{l}.$$

The Bishop method resolves the forces on the slice vertically:

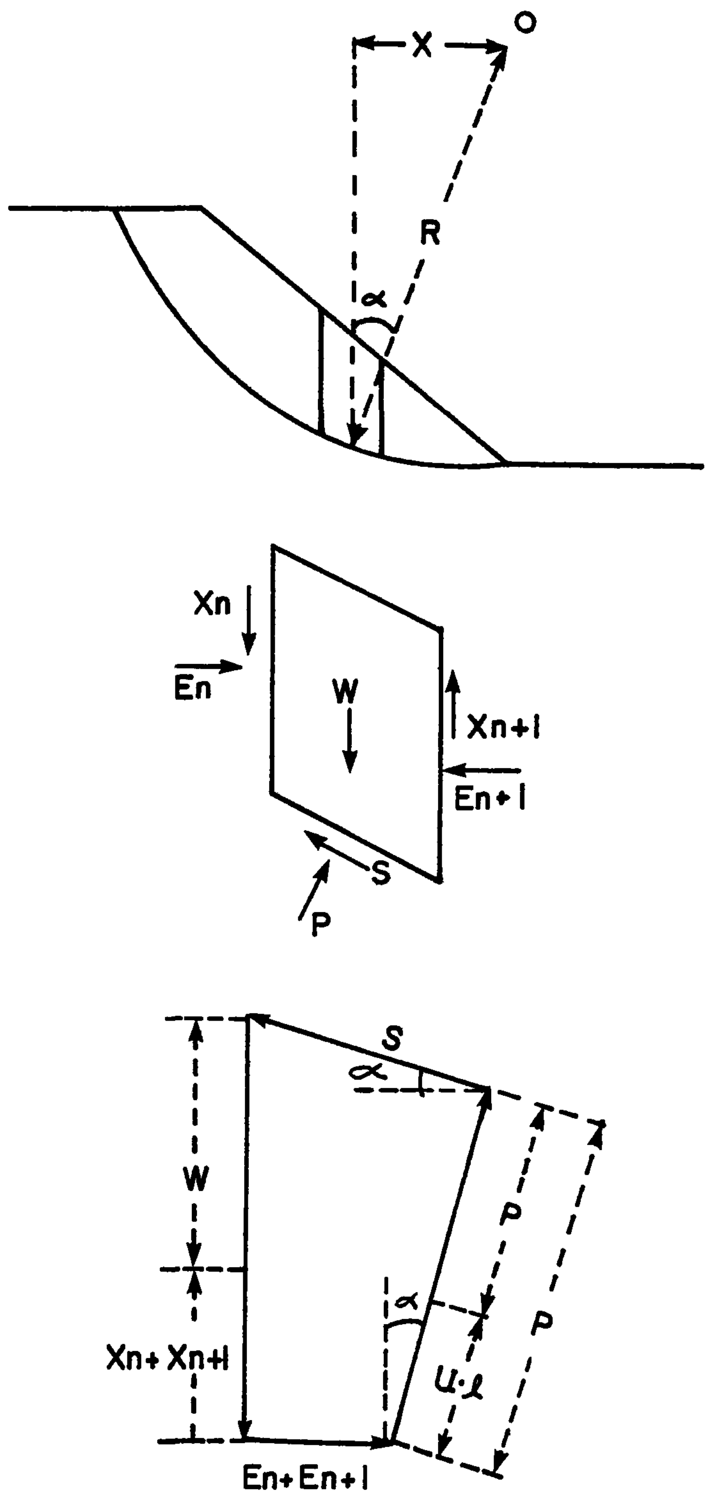


Figure 3.6 SLOPE GEOMETRY AND FORCE DIAGRAMS

$$W = P\cdot\cos\alpha + S\cdot\sin\alpha$$

$$P = \frac{W - S\cdot\sin\alpha}{\cos\alpha} = \frac{W - \frac{\tau'\cdot l}{F}\cdot\sin\alpha}{\cos\alpha}$$

and thus

$$\sigma_n' = \frac{W}{l\cdot\cos\alpha} - u - \frac{\tau'\cdot l\cdot\sin\alpha}{l\cdot\cos\alpha\cdot F},$$

and if $l = \frac{b}{\cos\alpha}$

$$\sigma_n' = \frac{W}{b} - u - \frac{\tau'\cdot\tan\alpha}{F}.$$

We thus obtain:

$$F = \frac{\Sigma\tau'\cdot l}{\Sigma W\cdot\sin\alpha},$$

where $\tau' = \left(\frac{W}{b} - u - \frac{\tau'\cdot\tan\alpha}{F}\right)$.

Since the σ_n' vs τ' relationship is a curve of undefined shape, there are two possible methods for resolving τ' and F.

a) Double Iteration method. Both τ' and F can be resolved by the iteration method since $\frac{W}{b} - u$ is a constant. This method first necessitates assuming an initial value for F, calculating the corresponding $\left(\frac{W}{b} - u - \frac{\tau'\cdot\tan\alpha}{F}\right)$ factor and determining by iteration the correct τ' shear strength from the Mohr-Coulomb envelope for each separate slice. The factor of safety for the entire sliding arc can then be computed using the assumed factor of safety, and then the assumed and computed factor of safety values are compared. This procedure is repeated until the assumed F value is reasonably equal to the computed safety factor.

This method is readily available with the use of high-speed computers, especially if an analytical solution is sought to resolve the true values of τ' and F. The true value of each of these expressions is given by the intersection of two lines, one representing the theoritical relationship between the assumed and computed values ($V_c = V_a$) which is a 45^o sloping line, and the other is defined by the actual linear relationship between assumed and computed values; the true value is then

$$V_t = \frac{V_{c1} - m \cdot V_{a1}}{1 - m}, \quad \text{where } m = \frac{V_{c2} - V_{c1}}{V_{a2} - V_{a1}}, \text{ and}$$

V_{c1} and V_{c2} are the computed values from the assumed values V_{a1} and V_{a2} (figure 3.7).

b) Analytical method. The second method for resolving the factor of safety necessitates the fitting of a curve to the Mohr-Coulomb envelope to express the σ_n' vs τ' relationship in algebraic form to resolve τ' in terms of W and u (function defining the equation of the curve). This can either be done by fitting a high-degree equation as previously described, or by assuming that the σ_n' function may be represented by a straight line (Coulomb's equation) or by a series of straight lines tangent to different points of the envelope; each line would in fact re-

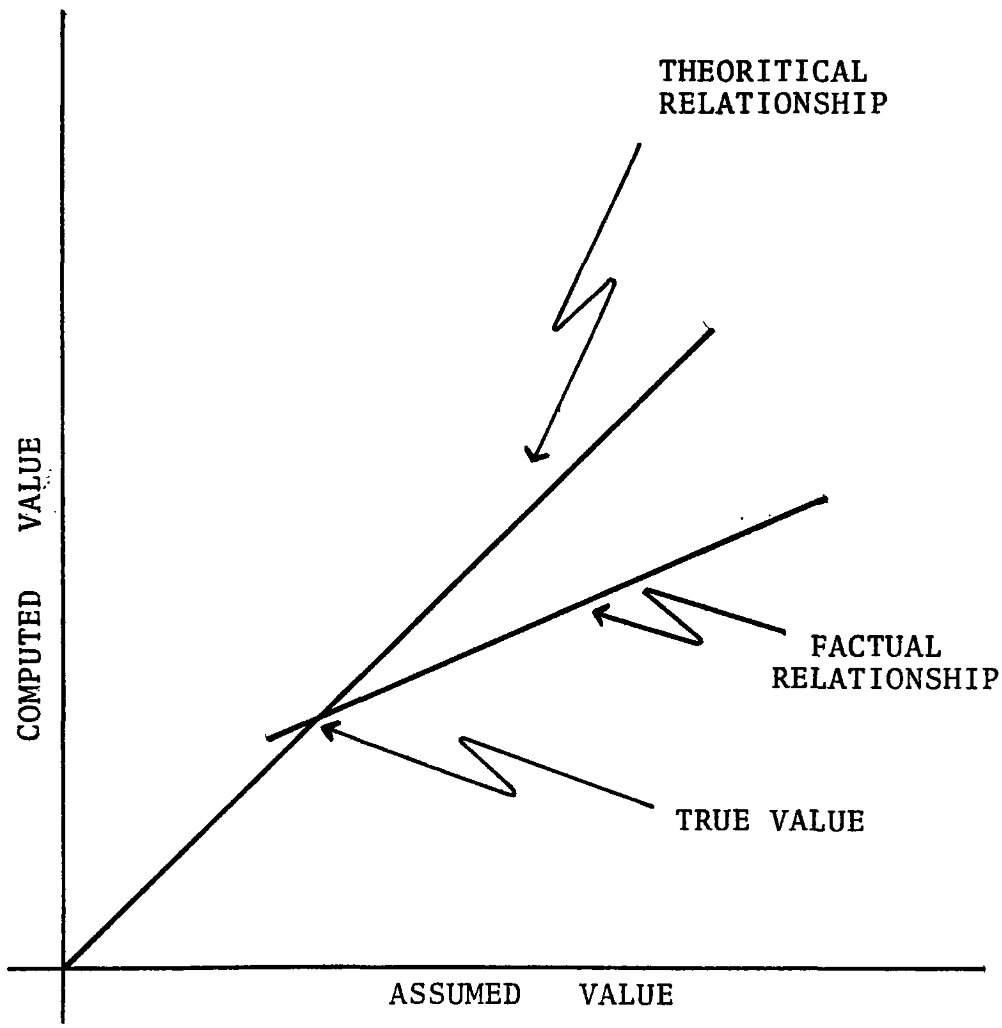


Figure 3.7 GEOMETRICAL SOLUTION TO RESOLVE AN ITERATION

present a definite portion of the curved failure envelope (as in the present computer program, and as shown on figure 3.5).

The equation for a linear representation of the function $\tau' = f(\sigma_n')$ is

$$\tau' = c' + \tan\phi' \cdot \sigma_n' \quad \text{(linear equation of the form } y = m \cdot x \pm b)$$

where c' is the Y-intercept and $\tan\phi'$, the slope of the straight line.

We thus have that

$$\tau' = c' + \tan\phi' \cdot \left(\frac{W}{b} - u - \frac{\tau' \cdot \tan\alpha}{F}\right), \text{ and}$$

$$\tau' = c' + \tan\phi' \cdot \left(\frac{W}{b} - u\right) - \frac{\tau' \cdot \tan\alpha \cdot \tan\phi'}{F}.$$

Thus

$$\tau' = \frac{c' + \tan\phi' \cdot \left(\frac{W}{b} - u\right)}{1 + \frac{\tan\alpha \cdot \tan\phi'}{F}}.$$

The factor of safety is then

$$F = \frac{\Sigma \dfrac{\tau' \cdot l}{1 + \dfrac{\tan\alpha \cdot \tan\phi'}{F}}}{\Sigma W \cdot \sin\alpha}$$

And since the value $\tan\alpha$ must always have the same sign on each side of the center of the failure arc, we get

$$F = \frac{\Sigma \dfrac{\tau' \cdot l}{1 + \dfrac{\left|\tan\alpha\right| \cdot \tan\phi'}{F}}}{\Sigma W \cdot \sin\alpha}$$

The factor of safety can then be resolved by a single iteration procedure.

CHAPTER 4

THE CONDITIONS AT THE THREE STUDY SITES

4.1 General

A general description of the conditions existing at the three sites examined by the parametric study is given. Geological and hydrogeological conditions are discussed and a brief review of the geotechnical properties is presented. Geochemical determinations made by the author are also discussed.

4.2 Location of Sites

The clays whose properties are examined in this report are from three geographically adjacent proposed bridge crossing areas in Russell County, south-east of Ottawa. The location of these sites is indicated in Figure 4.1.

The Bearbrook samples come from an area approximately 0,7 miles south of the village of Bourget on County Road no.8 in the Township of Clarence, United Counties of Prescott and Russell, Ontario.

The South Nation site lies about 4½ miles north of

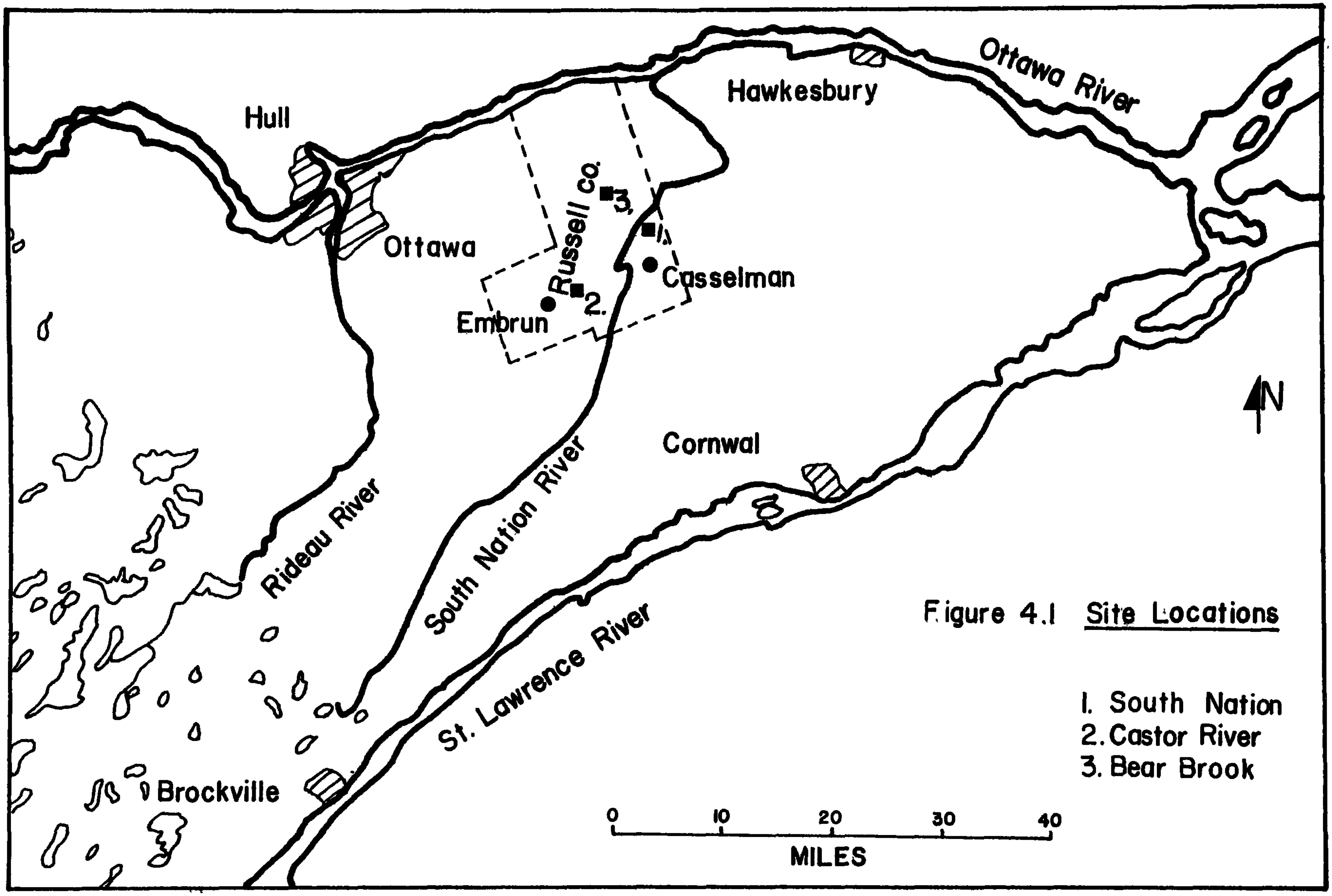


Figure 4.1 Site Locations

the town of Casselman, between concession II and III on a route segment uniting county roads no. 8 and no. 16, in Cambridge township, Russell county.

The Castor River area is at the proposed bridge site for county road no. 5, in lot 30, concession VI, in the township of Cambridge, United Counties of Prescott and Russell.

All quoted elevations refer to geodetic benchmarks.

4.3 Geology and Stratigraphy

These three sites lie in the physiographic region of the Russell and Prescott sand plains. A thin veneer of sand of variable thickness (up to 4.6 meters), covers the underlying Champlain Sea deposits, with a thickness of about 55 meters. The thickness of the Champlain Sea deposits is controlled by the underlying glacial till and limestone bed-rock topography. Deep gullies have been cut by rivers and streams, creating metastable clay slopes in an otherwise monotonous topography. Bedrock and till exposures in the river bottoms seem to control the river gradients and bed elevations. Failures of the clay valley walls, sometimes of large retrogressive flow types, are caused by base erosion of the slope walls and seem to be the main lateral erosion agent in these areas.

Stratigraphic profiles for all three sites, as established from boreholes logs, are shown in Figures 4.2a, 4.3a and 4.4a; Figure 4.5 is a idealized borehole log showing average index properties and field vane determinations for these sites.

At the South Nation river and Bearbrook localities, the plain surface elevation is approximately 190 feet (58 meters) A.S.L.. At Castor river, the surface is at an elevation of about 210 feet (64 meters) A.S.L.. Generally, the narrow valleys have steep walls with recent alluvial terraces eroded to one side at the base.

At the South Nation and Castor river sites, the top portion of the clayey horizon is altered to a stiff brown crust; this desiccated zone is not observed at Bearbrook where erosive processes probably removed this highly altered layer. At all three sites, the recent alluvium that irregularly mantles the clay deposit consists of loose gray sand generally containing silt and clay traces and organic plant matter; this sand mantle is weathered to brown at the surface. Both grain size distribution and mineralogical composition seem to indicate that this material originates from the erosion of the underlying clay. At the South Nation crossing, the layered intermixed nature of the sediments, as well as the presence of recent plant material at depth under the terrace on the west river bank, seem to indicate

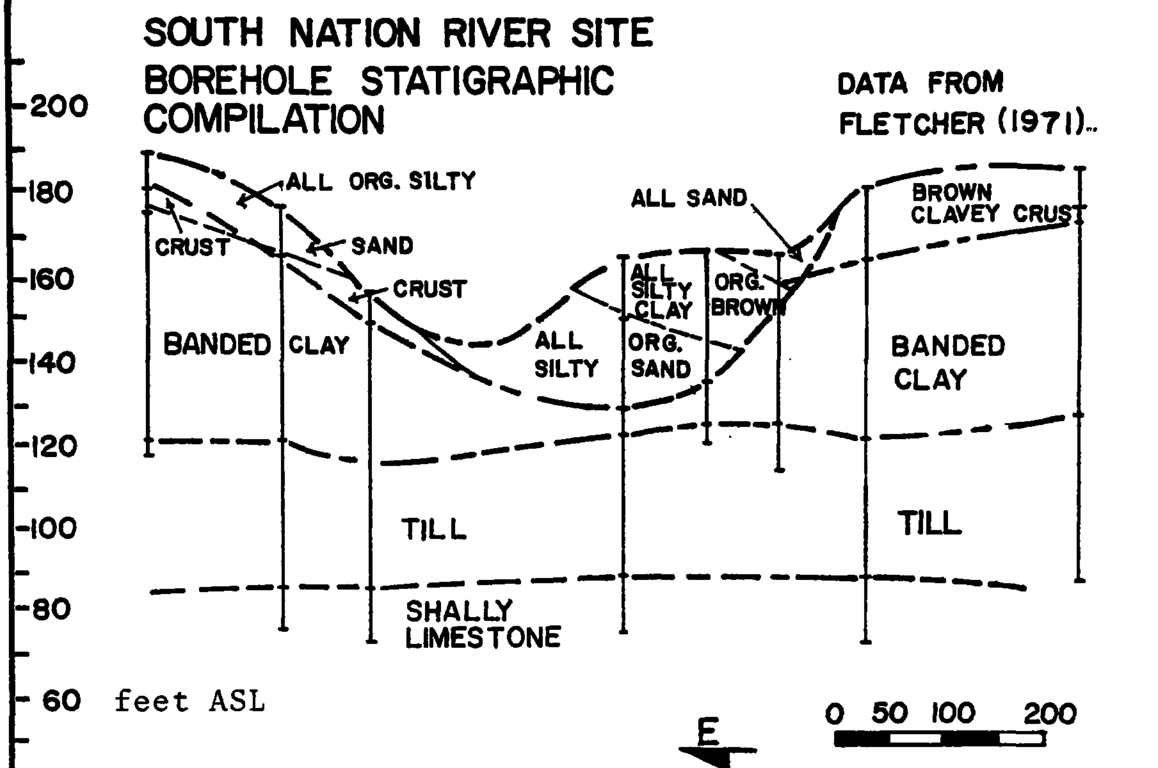


Figure 4.2 a

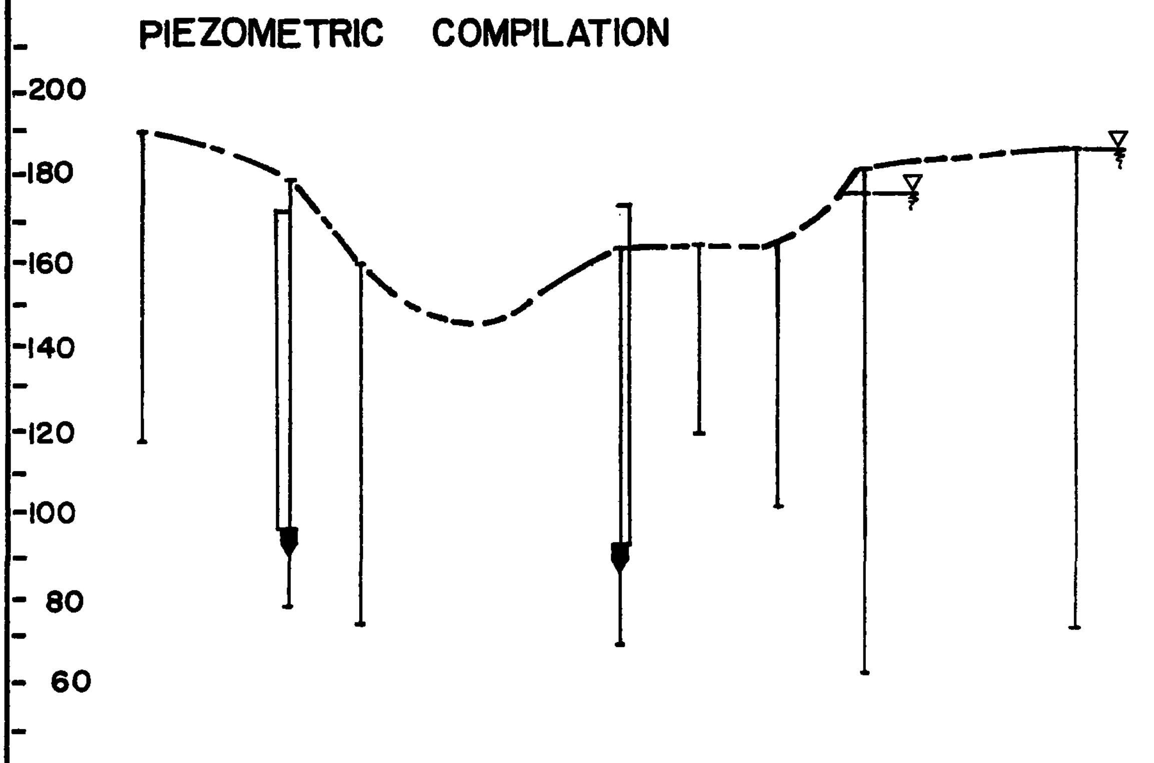


Figure 4.2b

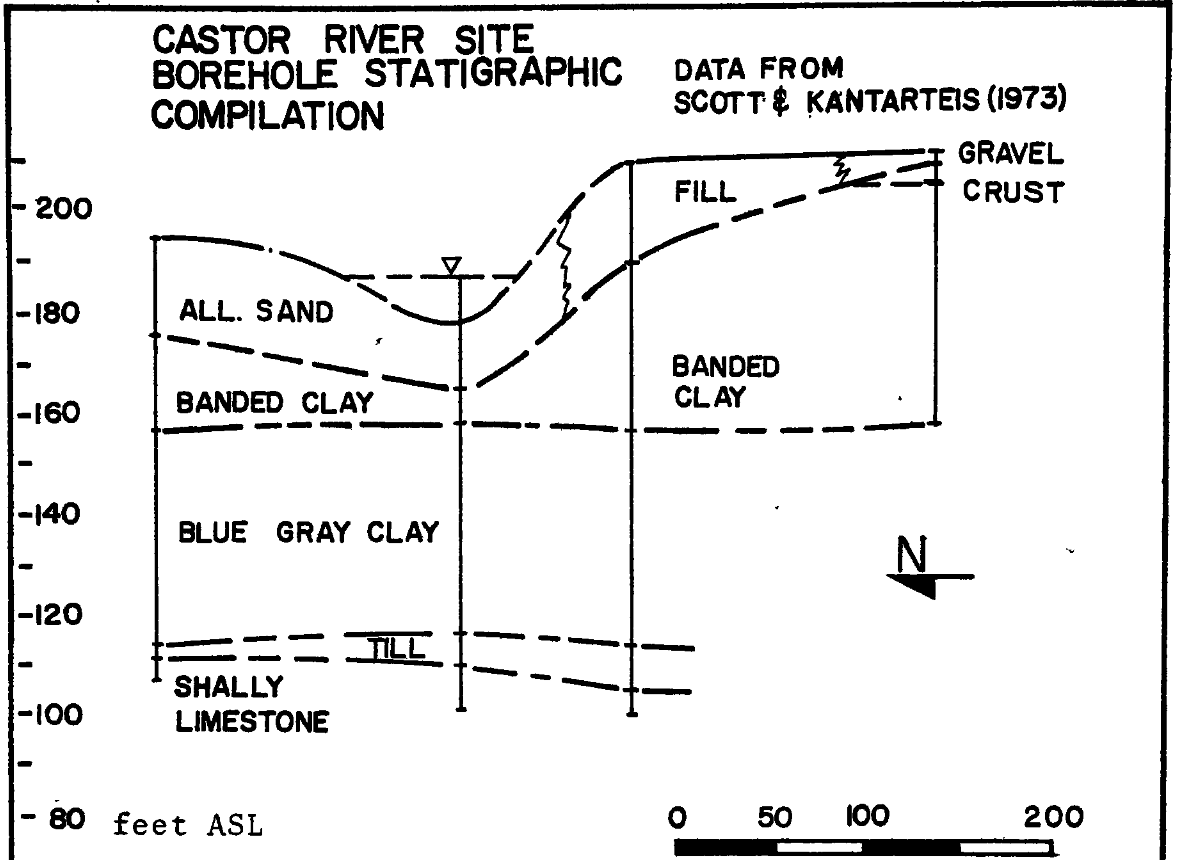


Figure 4.3a

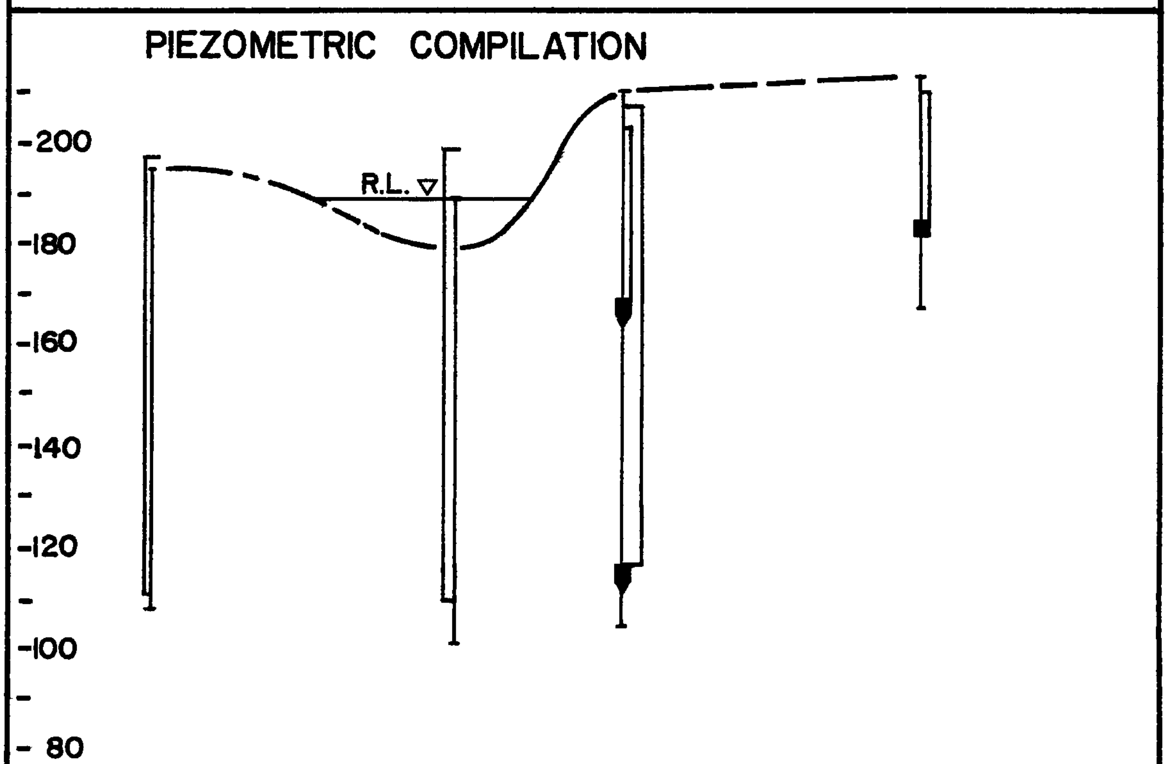


Figure 4.3b

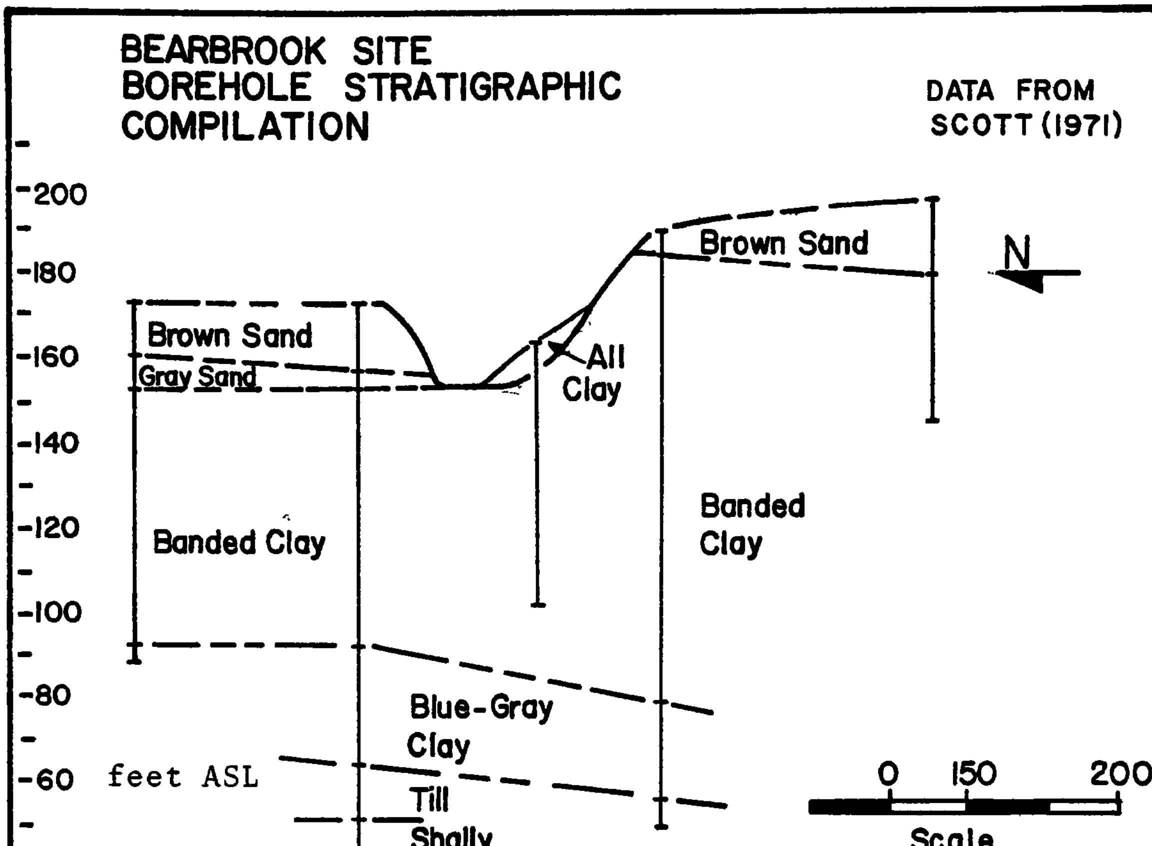


Figure 4.4a

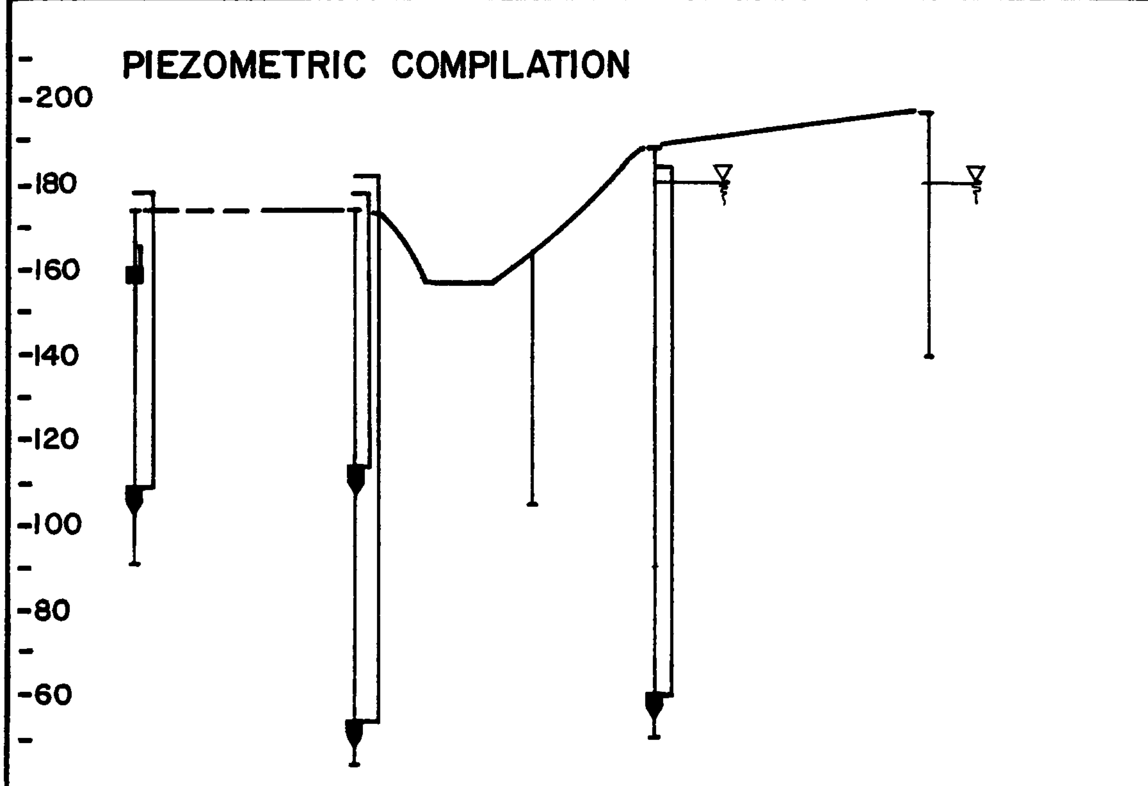


Figure 4.4 b

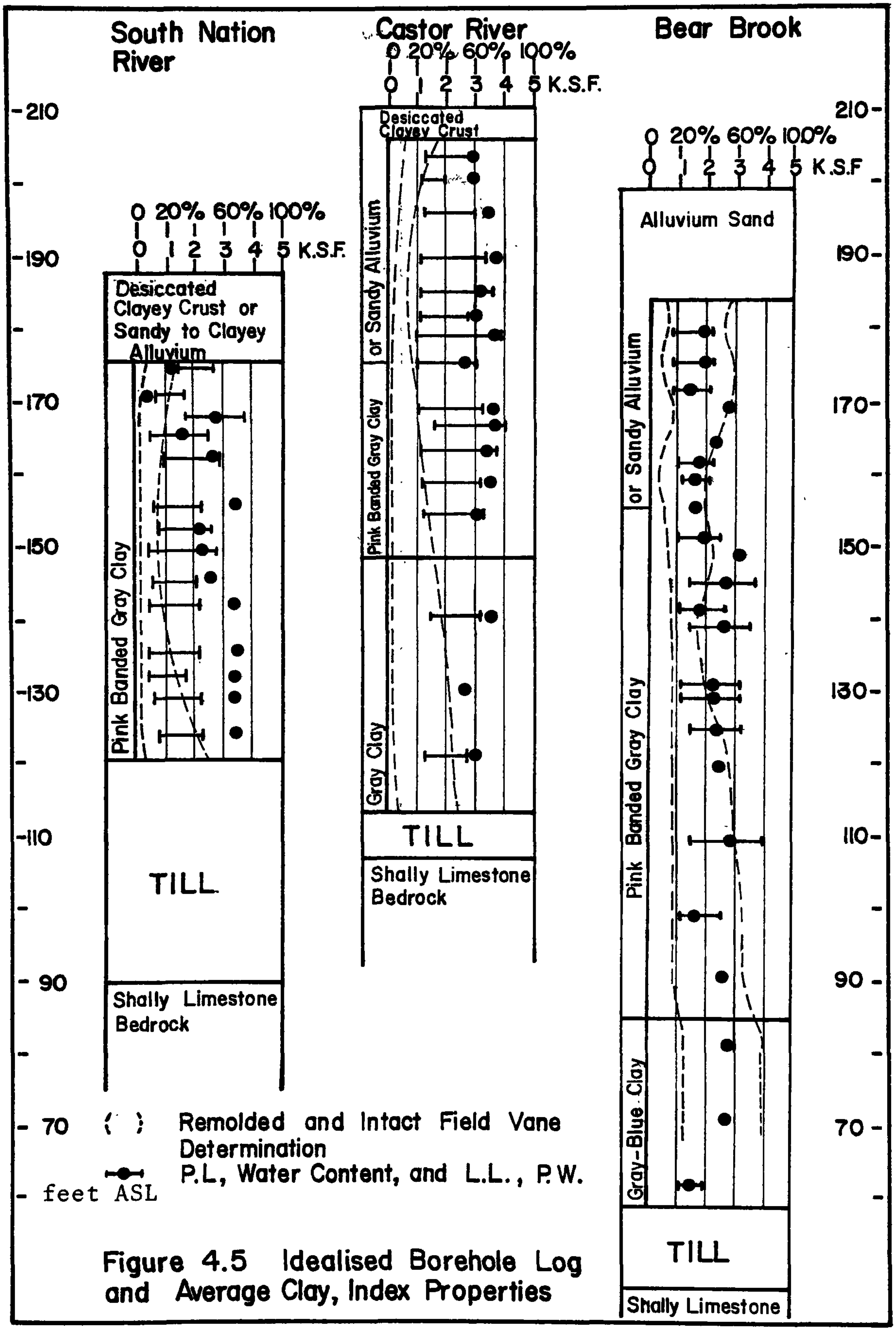


Figure 4.5 Idealised Borehole Log and Average Clay, Index Properties

that this terrace is built up of reworked material from an old landslide either close upstream or at the site itself.

Underlying the clayey crust and/or alluvial sediments, is a thick deposit of pink banded gray clay containing some sand and silt seams and black organic mottling. At Bearbrook and Castor, this banded clay grades with depth into a more uniform blueish-gray stiffer clay. A till horizon, composed of gravel to clay-sized particles, is sandwiched between the clay and the shaly limestone bedrock. The till contains some boulders, especially near the base.

Since the described stratigraphic sequences are all localized in the same plain cut by different river valleys, their surface topography is strongly dependant on local eluvation, erosion and alluviation processes, while the extent of the clay deposit at depth is controlled by the glacial history which governs the irregular till and bedrock levels. Since these three sites are geographically adjacent, the geological and geotechnical properties of the clay materials would be expected to be similar, though they show some major differences.

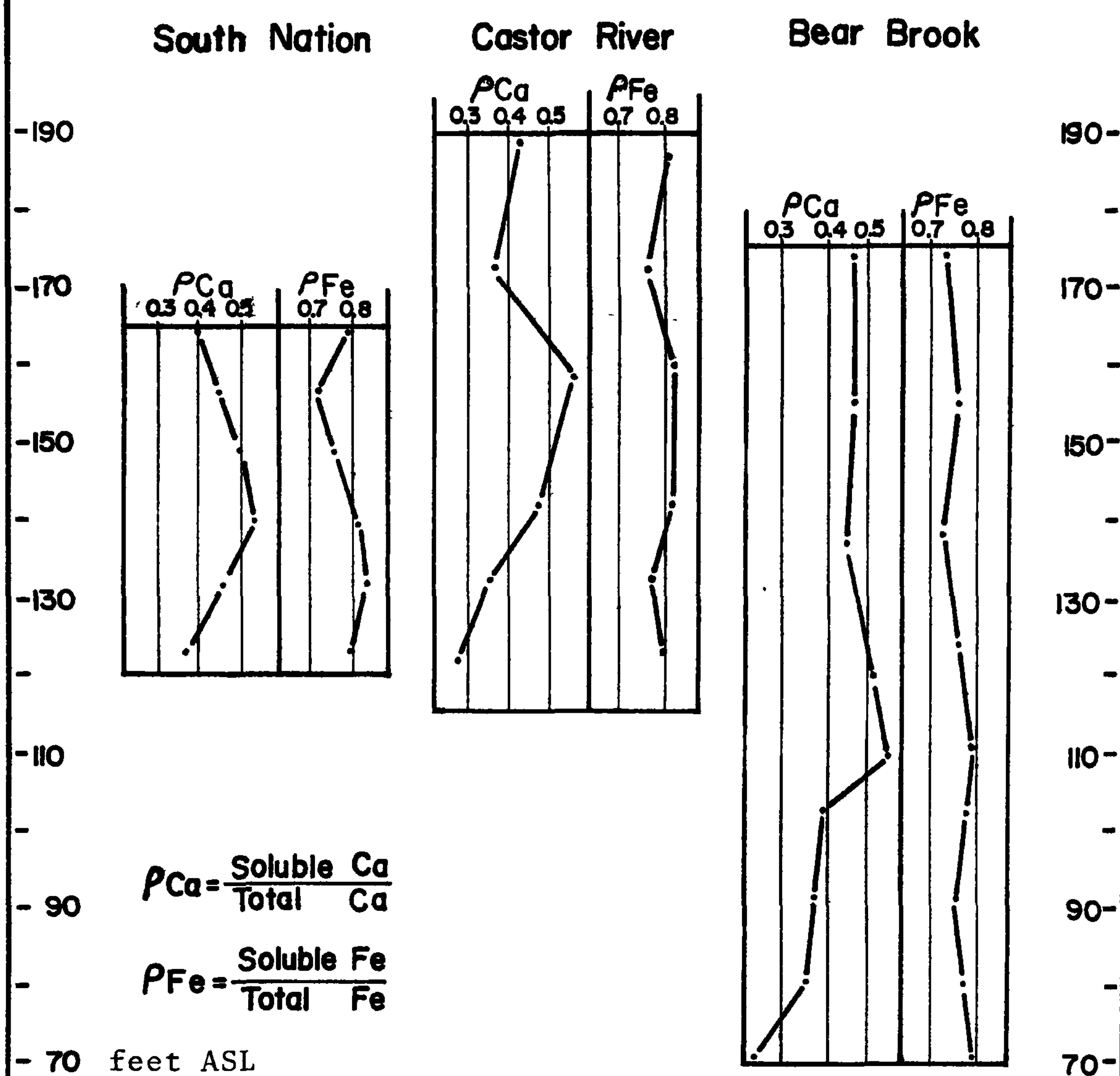
4.4 The Geochemical Characteristics

In an attempt to establish geological differences between the clays from the above mentionned sites, partial chemical characteristics of borehole and block samples were determined by the author in 1975 and 1976. No positive direct correlations have yet been described between the mineralogy-geochemistry and the shear behaviour of the Champlain Sea clays. Figure 4.6 shows the ratios of soluble calcium and iron to total element established from Shelby tube samples, as well as mean carbonate contents for block samples taken in the river bank at low water level.

The carbonate (calcite and dolomite) contents were determined with the use of a Chittick apparatus by the gasometric method described by Dreimanis (1962).

Soluble calcium and iron fractions were obtained by leaching oven dried samples with weak hydrochloric acid; total calcium and iron determinations were made on samples completely dissolved by the hydrofluoric-perchloric acid attack method. Analysis for the above mentioned fractions were done using the Department of Geology Atomic Absorption unit using standard procedures.

There is no noticeable trend at either sites for the variation of iron content with depth. Though no absolute correlation is indicated, there is an increase in the soluble to total calcium ratio with depth followed by a decrease. The inflexion point where this ratio trend changes from an increase to a decrease seems to correspond approximately



AVERAGE CARBONATE CONTENT
(From 18 Analyses)

	South Nation	Castor River	Bear Brook
Calcite	2.1 %	2.7 %	1.4 %
Dolomite	4.5 %	2.0 %	2.9 %
Total	6.6 %	4.7 %	4.3 %

Figure 4.6
SOLUBLE TO TOTAL RATIOS OF CALCIUM AND IRON
AVERAGE CARBONATE CONTENT

to the elevation where the vane shear strength starts to increase (Figure 4.4). There is thus a possible inverse correlation between soluble calcium and vane shear strength at depth.

Though there is no trend in either calcite or dolomite content from site to site, there seems to be an inverse relationship between total average carbonate content and the average shear strength measured at each site. The South Nation site, which has the weakest shear resistance, has the highest total carbonate content, while Bearbrook shows the lowest carbonate content and highest shear strength.

The present geochemical data may indicate the possibility of in situ weathering of calcium rich minerals and leaching of the soil as postulated by Sangrey (1972b). The increase in soluble calcium would correspond to an accumulation of the soluble fractions through leaching. The decrease in volume accompanying the weathering process would tend to fissure the soil as observed. The soluble calcium decrease would correspond to a less weathered and less fissured soil showing a greater shear strength. The above evidence seems to indicate that the weathering-leaching hypothesis presented by Sangrey is applicable to the present sites, though further testing is required to obtain a positive determination.

4.5 Hydrogeological Characteristics

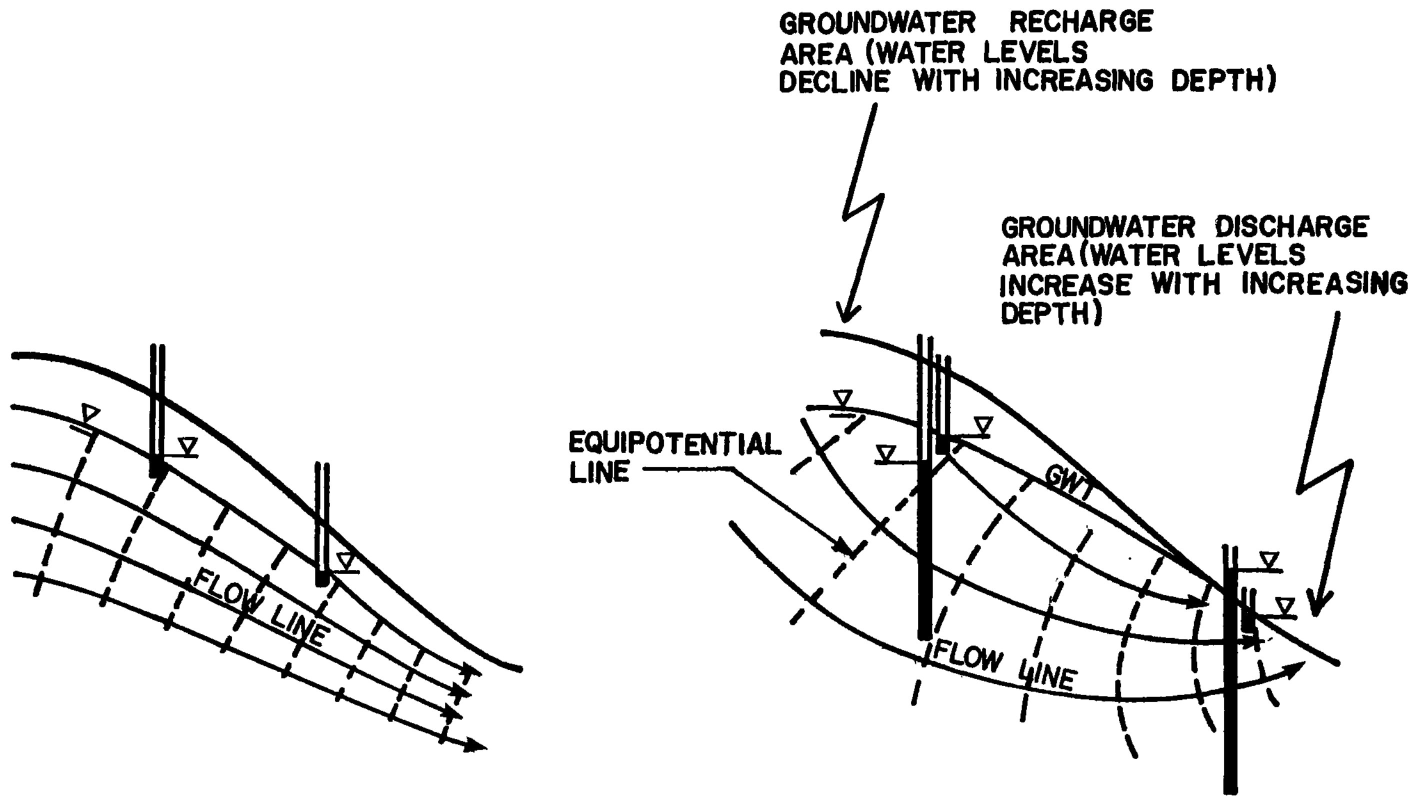
Figures 4.2b, 4.3b and 4.4b show the groundwater flow characteristics at each site inferred from maximum piezometer and standpipe measurements in the boreholes. All three sites show approximately the same type of flow. There is a strong downward component in the clay banks which seems to be drained by the more pervious till layer and fissured top portion of bedrock. The more impervious massive shaly limestone beds also are presumably drained by the till (groundwater recharge area). The till stratum usually exhibits strong to artesian groundwater conditions, especially near or under the river bed where porepressures are dissipated by an upward flow (groundwater discharge area): this is indicated by an increase in groundwater potential with depth and results in a near parallel to surface flow at shallow depths in the clay slopes. The piezometric level in the granular material below the clay seems to reflect the general groundwater surface in the overlying sand plain.

These observations are consistant with laboratory determinations of these clays where low horizontal to vertical permeability ratios in the order of 2:1 to 5:1 are observed (Laffont, 1977); these near isotropic conditions could allow for the observed flow types (Gélinas, 1976).

More detailed observations at other sites in the Ottawa area have also indicated the presence of this type of groundwater flow where similar stratigraphic and morphological conditions exist (Drouin et al, 1975). These conditions are thought to be much more generalized in the area than previously indicated.

Patton and Henderson (1974) have indicated that horizontal groundwater flow or flow parallel to the slope, as shown in Figure 4.7a, is seldom found in practice, and that a flow from recharge to discharge area (Figure 4.7b) is much more common in slopes of fairly uniform permeability. They stress the importance of establishing a detailed drainage pattern and obtaining a realistic profile showing not only the significant geologic structures but also the inferred porewater pressure acting on a potential or actual failure surface, because of the significant influence of the groundwater flow regime on the stability of slopes.

Scott et al (1976) discussed the importance of establishing a realistic flow net representative of the groundwater flow regime. Total shear strength being constant, in typical limit equilibrium slope stability analysis procedures, a decrease in cohesion, c', with a proportional increase in the internal friction angle, ϕ', tends to generate a shallower potential failure surface than a more cohesive near



A) GROUNDWATER FLOW ASSUMED PARALLEL TO GROUNDWATER TABLE (GWT) (SELDOM FOUND IN PRACTICE)

B) TYPICAL (NEOCLASSICAL) GROUNDWATER FLOW IN SLOPE (WITH UNIFORM PERMEABILITY)

Figure 4.7 COMPARISON OF GROUNDWATER FLOW IN SLOPES frictionless material. The resulting low normal stress in this shallow slip surface entails an increase in the influence of the groundwater flow regime, since the calculated factor of safety varies considerably with moderate changes in pore water pressures. It is evident that the observed groundwater flows have considerable influence on the behaviour of slopes and must be considered as important as the soil's shear strength characteristics.

4.6 Geotechnical Properties

Since this study is not primarily concerned with the index properties of these soils, only a brief summary of the soil properties is presented. A detailed description of the geotechnical properties of the clays at these sites can be found in Toombs (1973). A general resumé is presented here.

Due to the fairly level nature of the plain and the close localization of the sites, it would appear that the clays from these three sites would have similar properties, though in fact these vary widely.

Atterberg limits, water contents and field vane shear strengths are indicated along the borehole logs in Figure 4.5. In general, the less sensitive Bearbrook clay has a lower water content, well within the liquid limit, than the Castor and South Nation river clays. Similarly, the lower average plastic limit of the South Nation river clay probably indicates a lower clay content (Bjerrum, 1954). The very high water contents below the 140 foot level at the South Nation site are noteworthy. Where the desiccated crust occurs, the water content is low, close to or below the plastic limit.

The soil unitweights vary slightly in the South Nation area, showing the highest values (103 to 115 pcf or 1.6 to 1.8 g /cm^3. The Bearbrook and Castor sites show approximately the same values (104 to 108 and 101 to 108 pcf respectively, or 1.5 to 1.7 g /cm^3).

The standard deviations of the Atterberg limits and indexes for the soils on tables 4.1, 4.2 and 4.3 indicate that the South Nation river clay is much less uniform than the other two clays. The Castor river clay seems to contain more clay minerals due to the higher mean plastic index and plastic limits.

These mean values are plotted on the plasticity chart in Figure 4.8. This chart shows that the South Nation River clay has a medium plasticity, while Bearbrook and Castor clays show a high plasticity. All three clays are situated close to the "A" line indicating their silty or slightly organic nature.

Table 4.1 LIST OF ATTERBERG LIMITS AND INDEX PROPERTIES

South Nation River Site

	Pw	Lw	W	Iw	Il
	33	77	54	44	0.48
	12	51	35	39	0.59
	16	55	54	39	0.97
	16	47	70	31	1.74
	15	56	45	41	0.73
	15	56	47	41	0.78
	14	22	32	8	2.25
	18	43	47	25	1.16
	7	41	62	34	1.62
	8	42	66	34	1.71
	10	36	66	26	2.15
	7	41	69	34	1.82
	13	44	66	31	1.71
	21	35	57	13	2.77
	22	50	47	28	0.89
	18	33	47	15	1.93
	28	34	48	6	3.33
	34	49	50	15	1.07
	23	42	32	19	0.47
	25	38	23	13	-0.15
	16	23	50	7	4.86
	28	52	53	24	1.04
	24	57	62	23	1.65
	22	34	33	12	0.92
Σ	445	1058	1215	602	36.49
$\bar{X}$	18.54	44.08	50.63	25.08	1.52
σ	7.63	11.99	12.94	11.91	1.06

Table 4.2 LIST OF ATTERBERG LIMITS AND INDEX PROPERTIES
Castor River Site

	Pw	Lw	W	Iw	Il
	21	59	63	38	1.11
	27	77	74	50	0.94
	25	76	71	51	0.90
	28	81	78	53	0.94
	26	76	81	50	1.10
	30	71	70	41	0.98
	27	77	77	50	1.00
	27	81	78	54	0.94
	27	67	72	40	1.13
	29	78	71	49	0.86
	25	64	70	39	1.15
	27	80	76	53	0.94
	24	62	67	38	1.13
	22	74	73	52	0.98
	23	66	63	43	0.93
	22	68	63	46	0.89
	23	72	68	49	0.92
	26	66	66	40	1.00
	29	66	71	37	1.14
	26	57	61	31	1.13
	21	59	59	38	1.00
	20	39	61	19	2.16
	23	58	67	35	1.26
	24	61	72	37	1.03
	29	86	91	57	1.09
	23	55	56	32	1.03
	26	81	75	55	0.89
	26	73	67	47	0.87
Σ	706	1930	1961	1224	29.44
$\bar{X}$	25.21	68.90	70.04	43.71	1.05
σ	2.70	10.42	7.48	8.87	0.24

Table 4.3 LIST OF ATTERBERG LIMITS AND INDEX PROPERTIES

Bear Brook Site

	Pw	Lw	W	Iw	Il
	27	73	32	46	0.11
	32	75	46	43	0.33
	23	70	52	47	0.62
	23	50	37	27	0.52
	20	50	38	30	0.60
	27	70	50	43	0.53
	30	78	55	48	0.52
	30	76	58	46	0.61
	25	62	50	37	1.48
	17	36	30	19	0.68
	18	42	35	24	0.71
	20	42	32	22	0.55
	20	42	35	22	0.68
	28	75	51	47	0.49
	23	62	43	39	0.51
	22	45	33	23	0.48
	20	51	27	31	0.23
	22	53	46	31	0.77
	27	68	40	41	0.32
	21	46	39	25	0.72
	28	71	30	43	0.05
	22	51	36	29	0.48
	20	60	55	40	0.88
	28	78	57	50	0.58
	26	70	54	44	0.41
	23	77	50	54	0.50
Σ	622	1573	1111	951	14.36
$\bar{X}$	23.90	60.50	42.70	36.58	0.55
σ	4.03	13.68	9.67	10.37	0.27

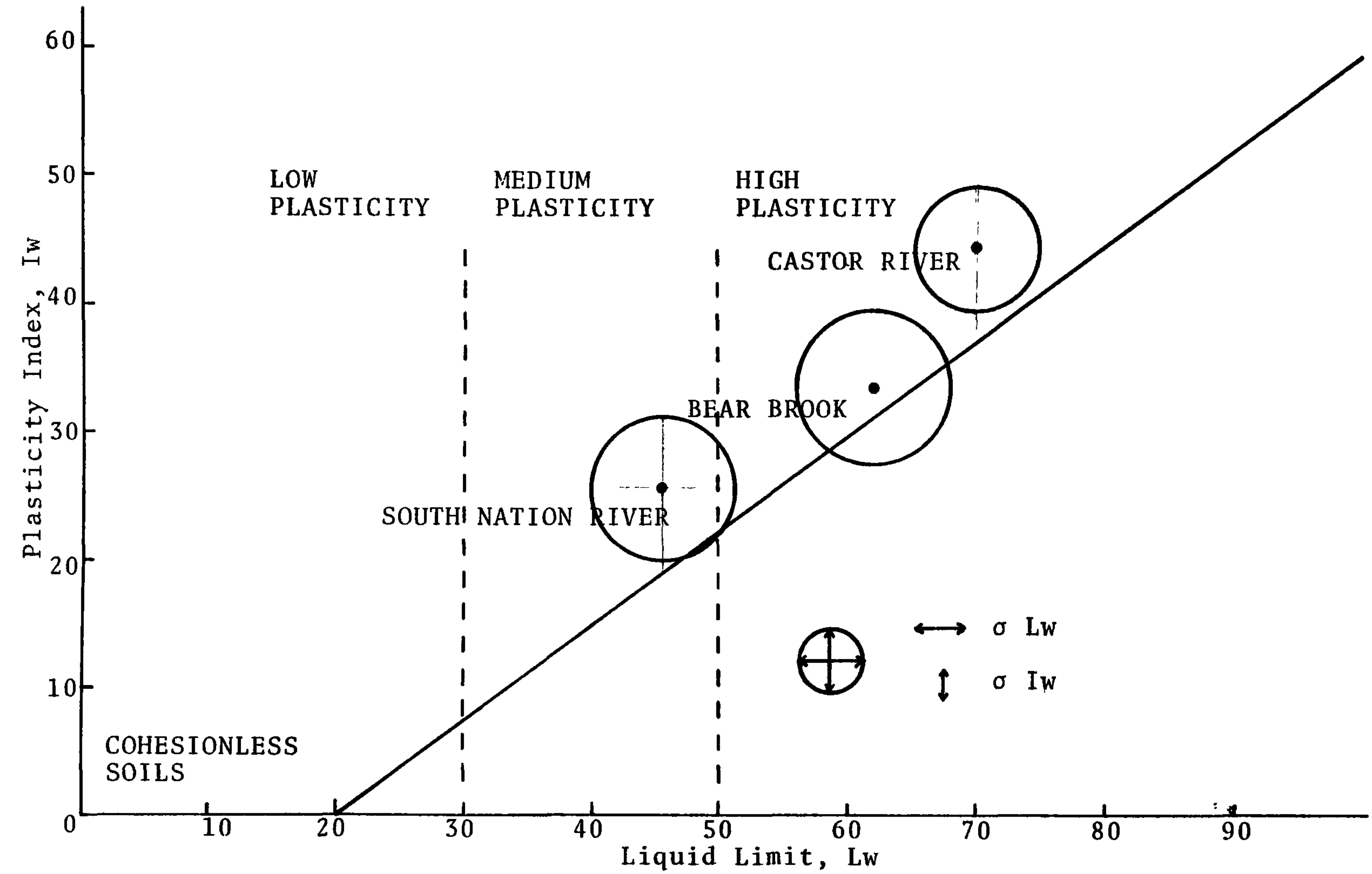


Figure 4.8 PLASTICITY CHART (CASAGRANDE)

Figure 4.9 shows a plot of all available field vane measurements with depth for all three sites. The field vane strength tends to decrease from the surface to well below the presumed high alteration zone (chemical or cement overconsolidation) then increases with depth (natural consolidation). The average low vane shear strength is approximately 0.75 KSF (36kPa) for Castor, 1.0 (48kPa) for South Nation and 1.7 KSF (86kPa) for Bearbrook.

Toombs (1973) indicated a field vane strength to preconsolidation pressure ratio of about 0.3 for all three sites except for one measurement at Castor River where the ratio is close to 0.6. It is noted that this sample was subjected to a large fill surcharge which would tend to increase the vane strength while decreasing the preconsolidation pressure due to a structural disturbance of the clay.

Crawford and Eden (1967) in an analysis of the Ottawa fissured clays, surmise that for a given elevation, the preconsolidation pressure measured at a number of sites should be approximately the same. Toombs (1973) indicated that the observations at the three above sites do not confirm Crawford and Eden's findings; it may be applicable to preconsolidation pressures measured at depths below the weathered zone, as demonstrated by the similar vane strength (1.7 KSF, 86kPa) at an elevation of about 130 feet (40 meters)

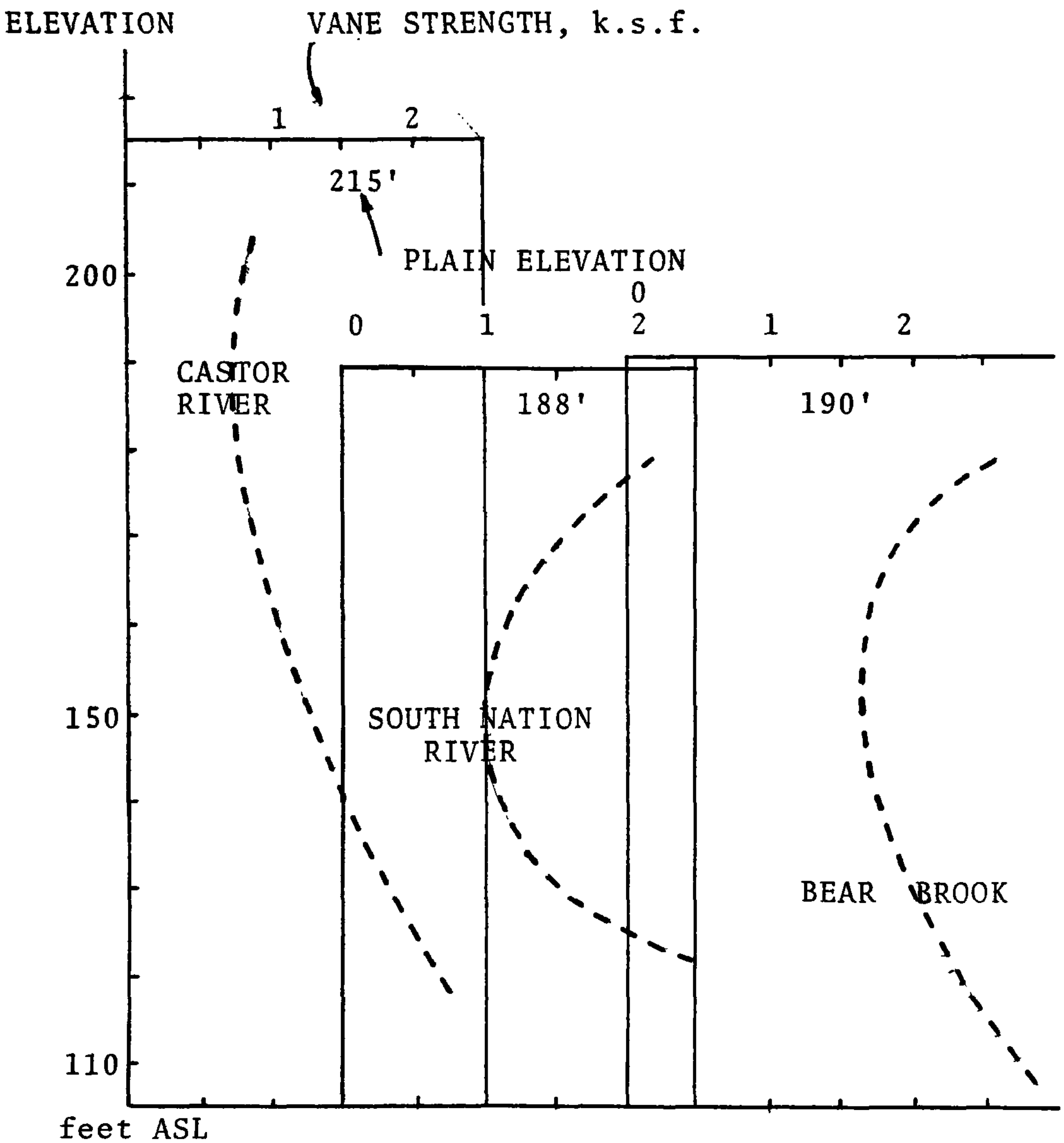


Figure 4.9 VANE STRENGTH AND ELEVATION

at all three sites. The portion below this elevation could possibly correspond to a normal consolidation zone while the upper zone would correspond to an area strongly affected by chemical weathering. The site showing the weakest vane strength could demonstrate a different degree of chemical action than that at the strongest site.

Figure 4.10 shows the p'-q' plots and effective normal stress-effective shear strength relationship determined by Toombs for the three sites. These envelopes are summarised in Figure 4.11.

As previously discussed, these fissured clays show a small or no cohesive intercept at an effective normal stress of zero, though no testing was done in the very low stress range and thus it is not known if the envelope passes through the origin.

The clay's shear strength behaviour at $\sigma_n' = 0$ will be discussed further in chapter 5.

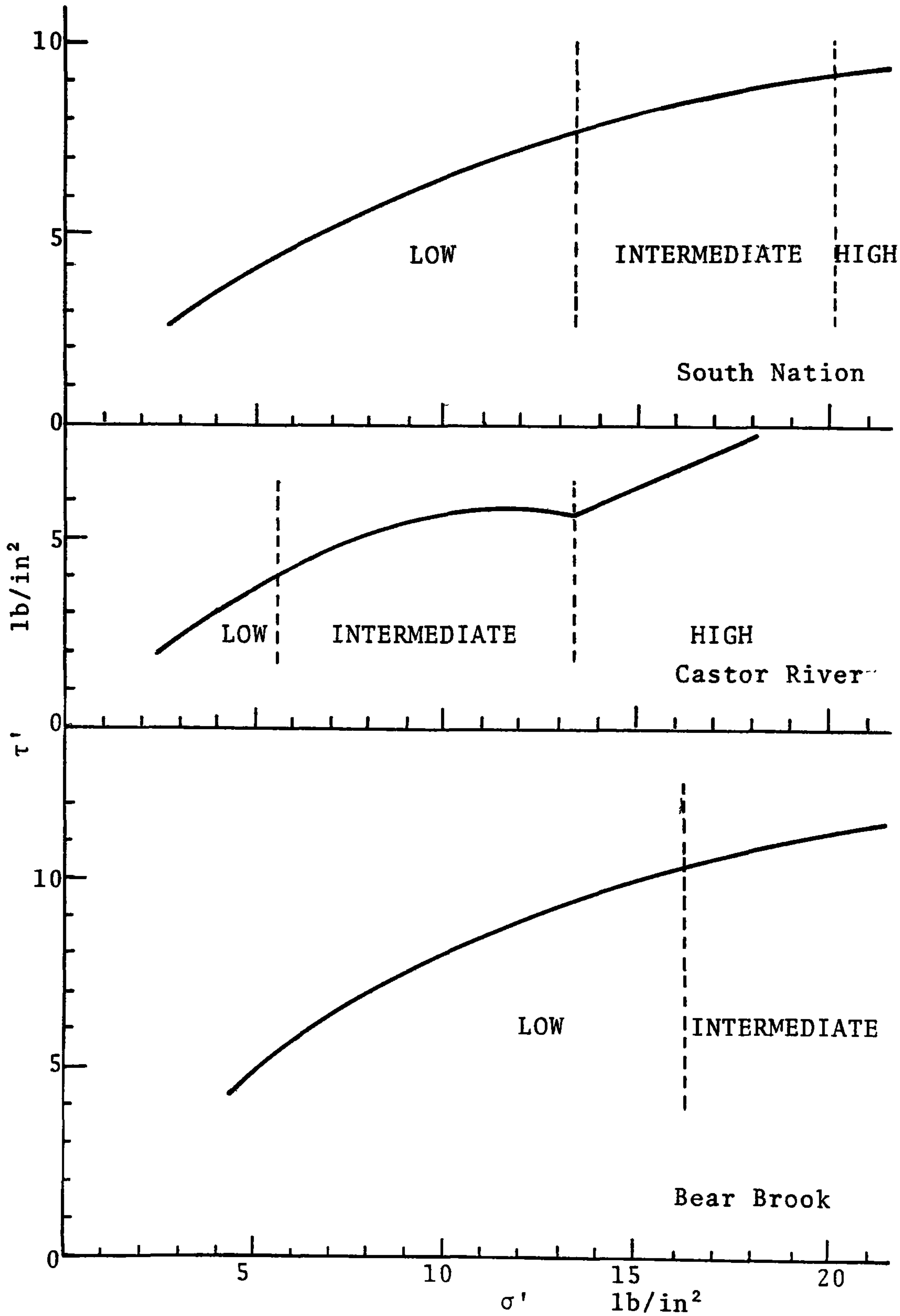


Figure 4.10 STRESS RANGES from Toombs (1973)

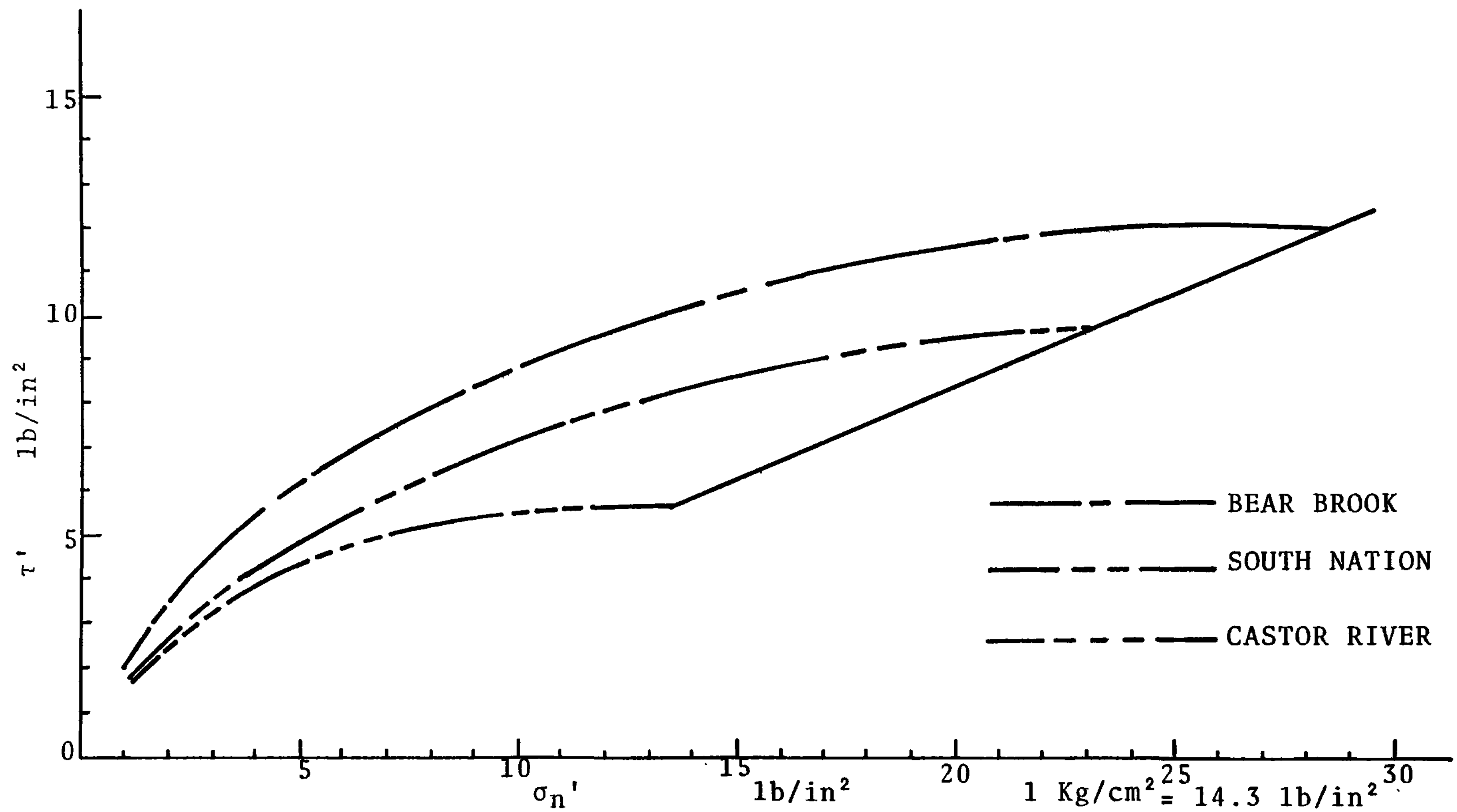


Figure 4.11 τ' vs σ' FAILURE ENVELOPES

CHAPTER 5

PARAMETRIC ANALYSIS

5.1 General

Slope failures in the Champlain Sea clay present a major construction problem in Eastern Canada, especially in the more densely populated areas, such as the Ottawa low-lands, where efficient land management is a very important aspect of regional development Land management is only possible through the use of "tools" condensing a wide information spectrum, of which geological and geotechnical maps are an important part.

Slope stability considerations could best be delt with by the use of general "factor of safety" maps covering the problem areas. Such maps have been prepared in the past, but it is suggested that the assumptions used in the analysis may oversimplify and distort the slope stability conditions existing at many sites.

The stability of slopes can be related to three major factors which will be discussed in this chapter:

1o the slope and subsoil geometry,

2o the soil's resistance to shear forces, and

3o the groundwater flow characteristics within the slope.

The slope surface geometry is established by a general survey of the area. The subsoil geometry is inferred from borings and surface geological observations in the area adjacent to the site. The soil's shear behaviour can be evaluated by in-situ or laboratory testing. All of the above factors depend on the geological history of the site.

The knowledge of the characteristics and of the influence of the groundwater flow in clay slopes of the Ottawa area has increased considerably in the past few years; porewater pressure distributions seem to be typically related to the subsoil stratigraphy as well as regional flow characteristics.

This chapter discusses the above mentioned parameters as applied to a general stability analysis of slopes in the Ottawa area. The present study should permit a better evaluation of the interinfluence of the three main parametric variables:

- geometry of the slope,
- shear characteristics of the soil and
- groundwater flow.

The relationship between the slope height and gradient has been studied by previous researchers.

5.2 Past Studies

In an effort to allow for a more efficient planning and development of the area south-east of Ottawa, Klugman and Chung (1976) made a general engineering geology study to semi-quantitatively classify the slope of this area as to their failure potential. In this study, no in-situ testing or observations other than slope measurements were made, and two of the three main variables controlling the performance of natural slopes were fixed as constants. The analysis was conducted assuming average low stress range soil shear strength parameters of 33° for the effective angle of internal friction (ϕ') and 200 PSF (98 Kg/square meter) for the effective cohesion (c'). The analysis further assumed hydrostatic groundwater conditions which are presumably the worst conditions typical of the spring period when slope failures occur. The results of this study are summarized in Figure 5.1.

Two of the basic assumptions made in this study may be questioned as to their validity. As previously indicated, the soil shear strength is extremely variable from site to site and the selection of a single set of parameters to describe the soil's shear performance in the entire region is questionable. Furthermore, observations have proven that the assumed hydrostatic porewater pressure distributions is not typical of the worst possible conditions that may exist.

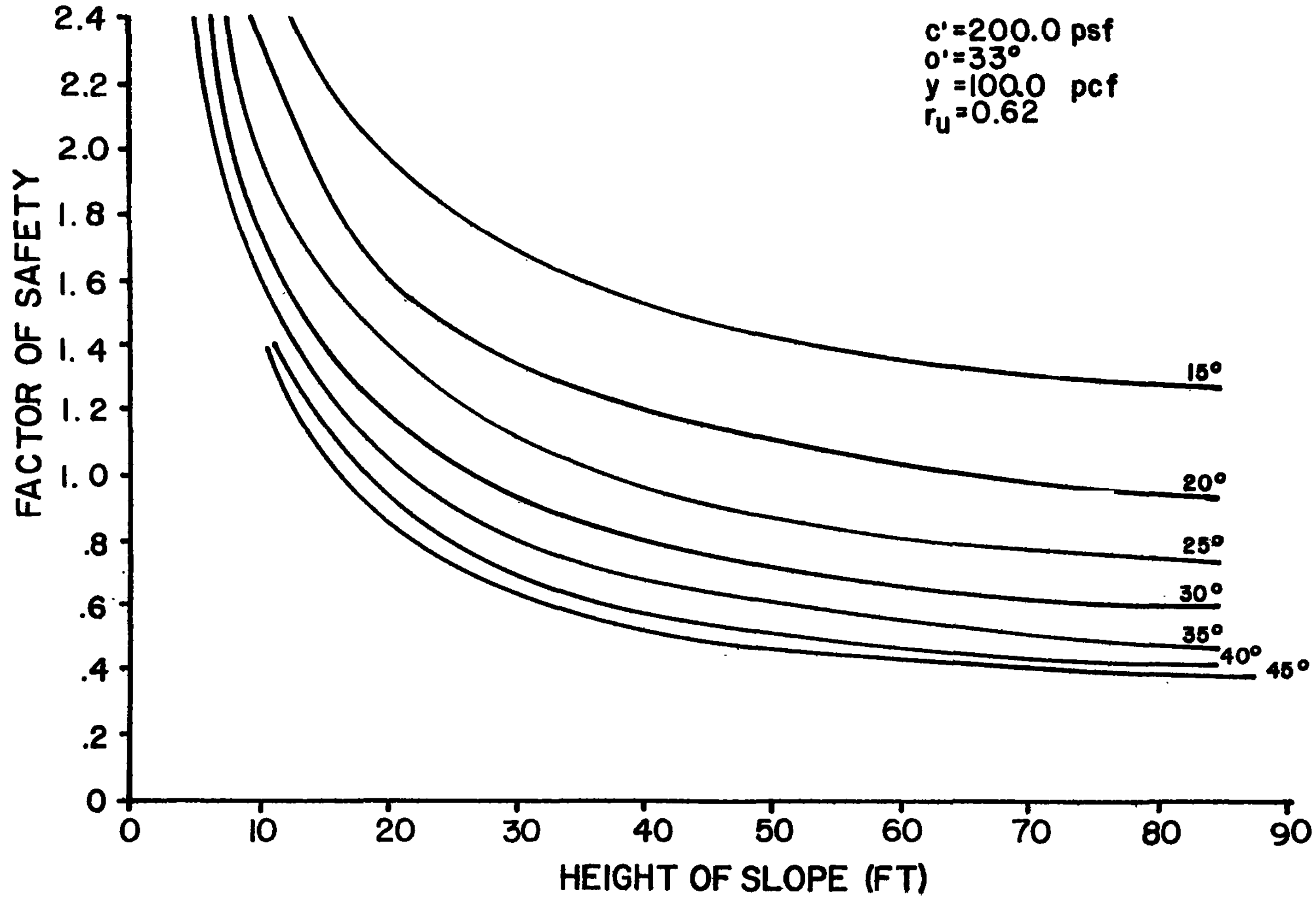


Figure 5.1 Relationship between the factor of safety and the slope height for different slope gradients of the Ottawa area.
(from Klugman and Chung, 1976)

Lafleur (1978) and Fransham (1978) made parametric studies of specific slopes in the Champlain Sea clays with in-situ piezometric observations. Both these studies have indicated much more variable groundwater flow conditions then the homogeneous flows normally assumed in classical geotechnical engineering analyses. The subsurface water flow systems observed in these studies corresponded to the flow nets inferred from piezometric observations made at various sites in the Ottawa area; the flow systems vary from artesian to downward flow conditions. For each site analysed in the two above mentioned studies, linear shear strength parameters were established from laboratory testing, and subsurface stratigraphy were determined by field observations.

5.3 Slope Geometry

The amount of variation in the factor of safety value entailed by a change in either shear strength or groundwater flow type for different slope geometries should be examined to evaluate this range of variation.

The results of the parametric study given in Figure 5.1 show a slope heigth to factor of safety relationship for different slope gradients suggested for the National Capital region. These results have served as a guide in the present study to choose slope geometries corresponding to moderately low, intermediate and moderately high slopes representing the range of typical design heights at a factor of safety near unity. The resulting slope surface geometries (30 feet at 1:1.75, 50' at 1:2.5 and 70' at 1:3) are illustrated in figures 5.2, 5.3 and 5.4 respectively.

The study of these three height dependant slope geometries in the parametric investigation will presumably allow to establish an approximate relationship between the effect of various slope geometries on the factor of safety for different sets of conditions. This will possibly permit to determine if a lower slope requires a less critical evaluation of the soil's shear behaviour and of the acting porewater pressures than do higher slopes.

5.4 The Soil Shear Strength Parameters

5.4.1 Evaluation of the Linearly Approximated Envelope

The curved stress-strength relationship shown by the Champlain Sea clays' shear behaviour has been extensively discussed in chapters 3 and 4.

Though the inapplicability of determining the soil's shear strength at low stresses by extrapolating its

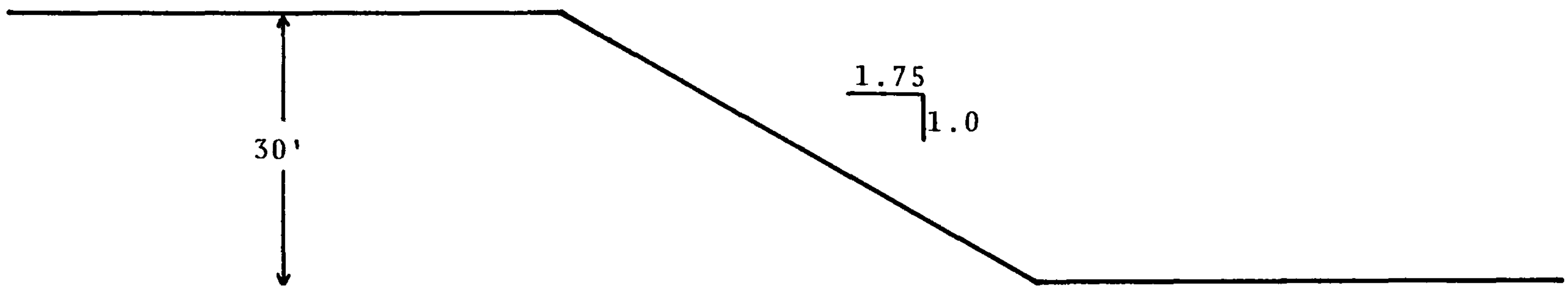


Figure 5.2 ASSUMED SLOPE GEOMETRY FOR PARAMETRIC STUDY: HEIGHT 30 FEET, SLOPE 1.75:1 .

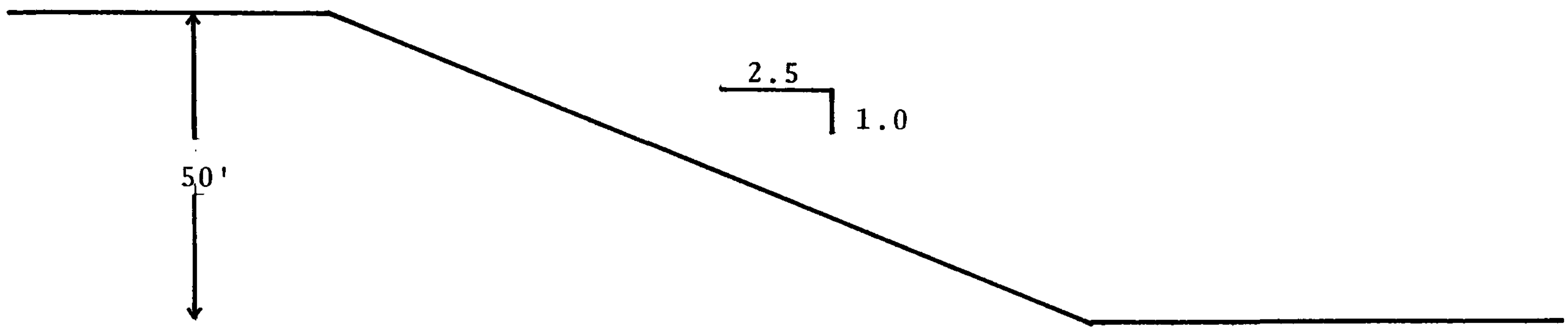


Figure 5.3 ASSUMED SLOPE GEOMETRY FOR PARAMETRIC STUDY:
HEIGHT 50 FEET, SLOPE 2.5:1 .

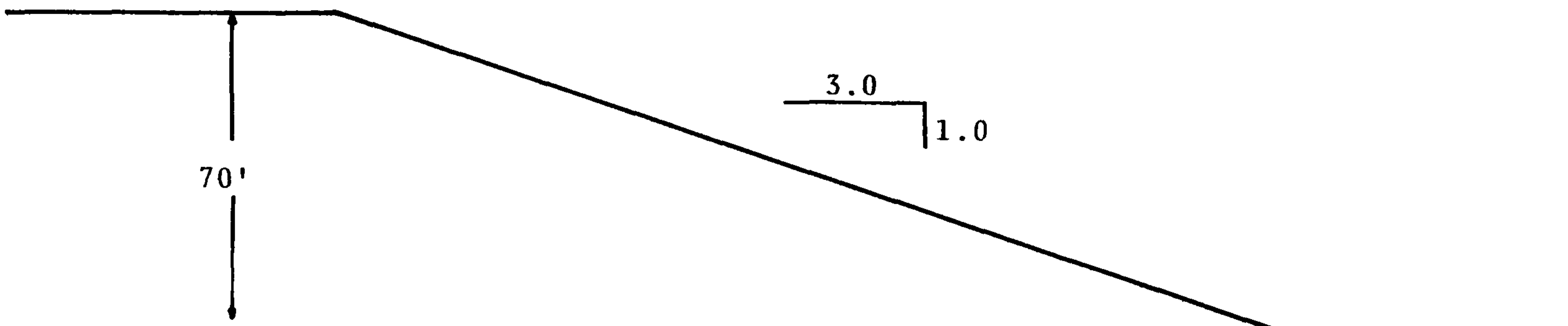


Figure 5.4 ASSUMED SLOPE GEOMETRY FOR PARAMETRIC STUDY:
HEIGHT 70 FEET, SLOPE 3:1 .

behaviour in the intermediate and high stress range has been proven, the need to evaluate the shear strength parameters from a curved Mohr-Coulomb failure envelope may still be questioned Since slope failures occur under low normal stress conditions, the classical method of representing the soil's shear strength by a single set of c' and ϕ' values may adequately describe the material's behaviour in this effective range.

McEnery (1978), in a study of the behaviour of Leda clay from different sites of the Ottawa area, suggested than an intermediate line between the tangent and the secant to the curved Mohr-Coulomb failure envelope, over the stress range expected on a potential failure surface, is sufficiently representative of the shear strength for stability analysis purposes. This normal stress range in usually limited between a near zero value and about half the preconsolidation pressure.

Scott et al (1976) indicated that a slight variation in porewater pressure will entail, at near critical effective conditions, considerable variations in the computed factor of safety value for a given slope. This variation in the critical state emphasizes the importance of an exact evaluation of the soil's low stress shear strength.

The present part of the parametric study will use the three different Mohr-Coulomb envelopes obtained for the Castor river, Bear brook and South Nation river sites. Both the true curved envelope and the approximation described by McEnery will be analysed (Figures 5.5, 5.6 and 5.7). The comparison of the results from the above shear strength values will give an indication of the influence on the factor of safety of the use of the true failure envelope compared to the use of an average value; it will also permit to evaluate the sensitivity of the factor of safety to what may be considered minor variations in the soil's strength properties.

5.4.2 The Cohesionless Failure Envelope

The use of a τ-intercept equal to zero to describe a soil's shear strength behaviour in a slope stability analysis based on the Bishop expression tends to generate for the most critical failure surface extremely shallow soil wedges parallel to the slope surface. This type of analytical solution is correct since the purely frictional nature attributed to the soil will define the weakest shear strength at an effective normal stress tending toward zero.

The failure surfaces associated with these extremely low safety factors have been termed unrealistic since they are not generative of slope failures; they may at best

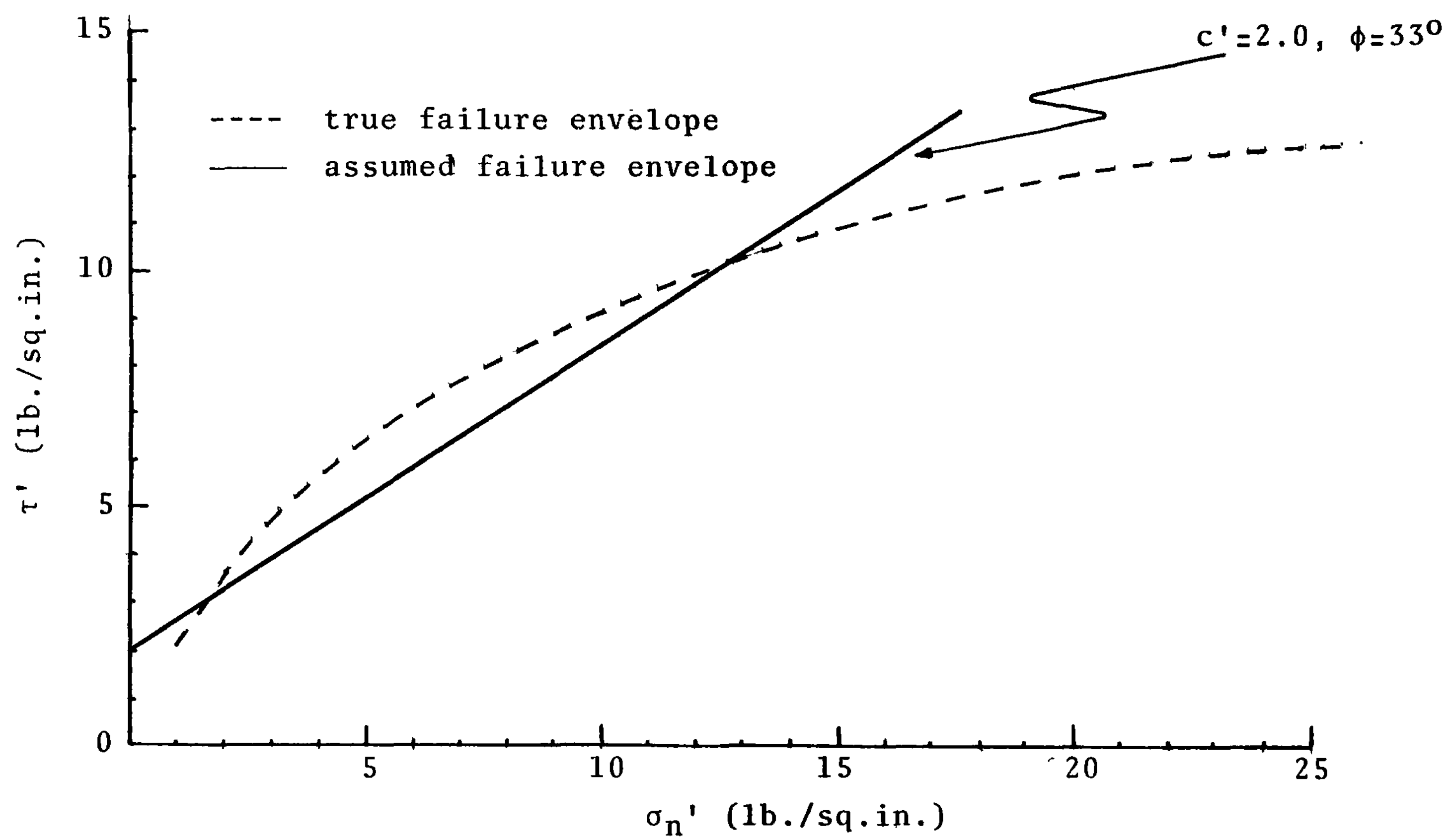


Figure 5.5 BEARBROOK - TRUE vs ASSUMED FAILURE ENVELOPE

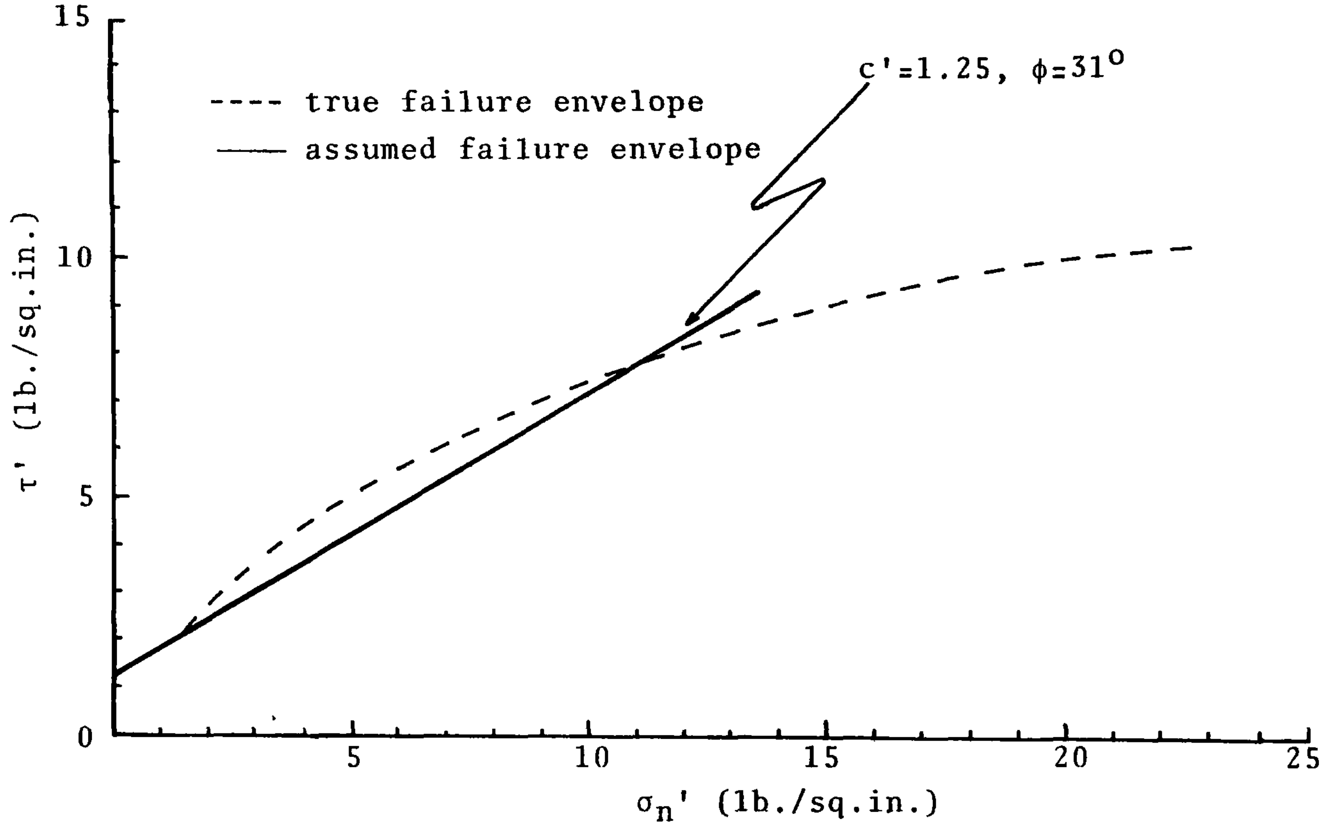


Figure 5.6 SOUTH NATION RIVER - TRUE vs ASSUMED FAILURE ENVELOPE

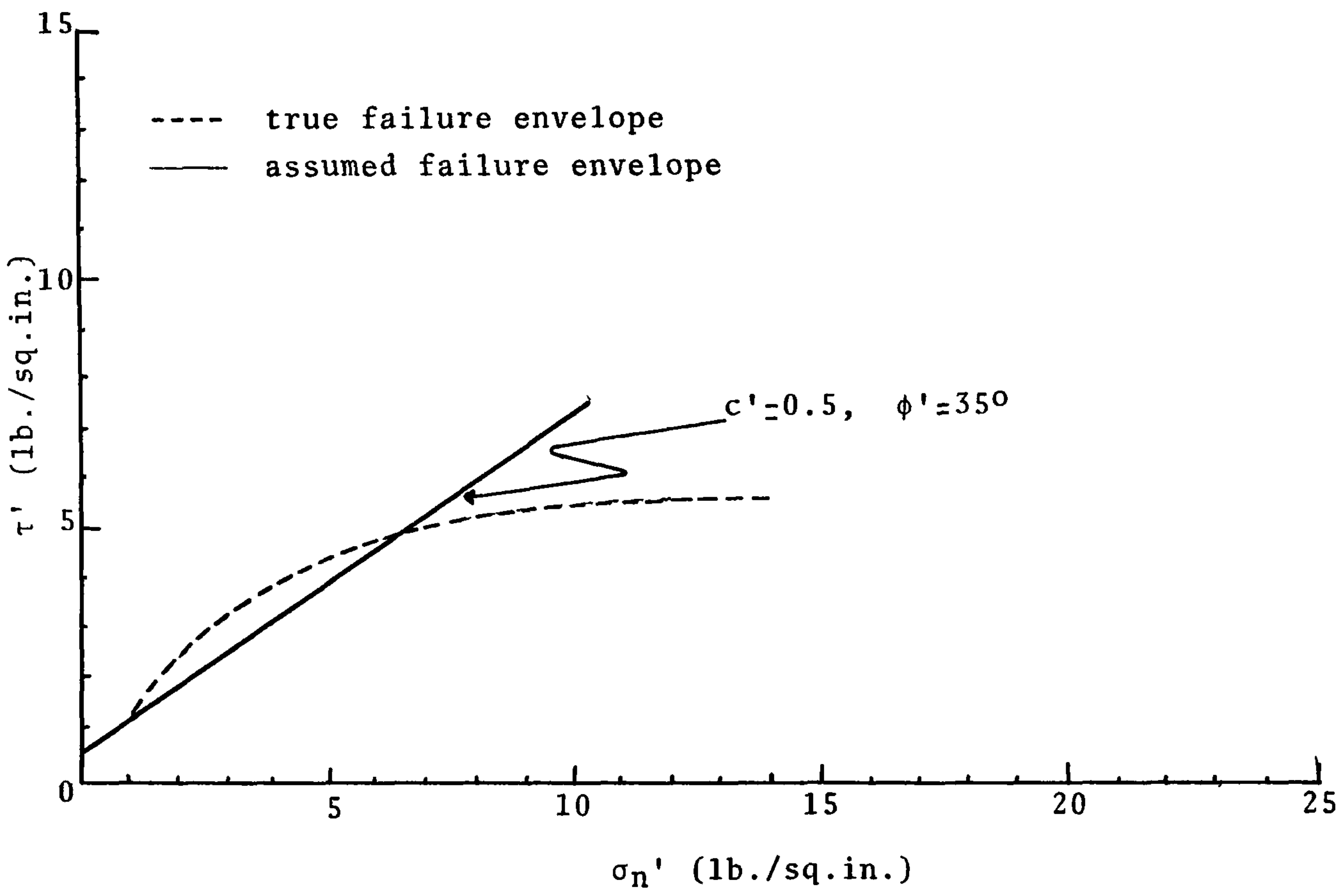


Figure 5.7 CASTOR RIVER - TRUE vs ASSUMED FAILURE ENVELOPE

be associated with the saltation or surface erosive processes observed on slopes during periods of high run-off.

It is common procedure in stability analysis to assume that the soil properties of the uppermost geologic unit and the groundwater conditions inferred from in situ observations extend to surface. This assumption may be misleading since it totaly ignores the stabilizing effect of the surface alteration zone. It is well recognized that the Champlain Sea clays are composed at surface of an irregular layer of weathered and disturbed material; sampling for laboratory determinations is usually done below this zone. The matèrial in this altered layer is very stiff to brittle and heavily fissured on both small and large scales; it does not show the same shear and hydraulic conductivity properties as the subjacent soil from which its behaviour is extrapolated. Such differences in soil behaviour, principally hydraulic conduction, may even be assumed to exist on freshly exposed clay slopes, such as landslide scars, where dilatation due to material removal may cause considerable fissuring in the superficial horizons.

The extent of this horizon is geologically negligeable but may have considerable influence on shallow failure surfaces. A stiffer upper material would increase the overall slope shear strength, and its fissuring would not allow for a sufficiently high porewater pressure buildup to obtain zero effective normal stresses near the slope surface. The highest possible porewater pressures in an open system such as the one presented by the upper fissured horizon would correspond to hydrostatic state; the conditions favoring this state are only possible in prolonged periods of high run-off when complete saturation of this zone is attained. This zone in fact acts as a dissipation zone for the high porewater pressures below. Even at saturated conditions, a few feet of this type of material would transmit to the underlying soil sufficient effective stress to attain conditions well in excess of $\sigma_n'=0$ near the slope surface.

Due to the lack of engineering significance of the shallow failure circles generated by a $c'=o$ analysis, it is presently suggested that the use of a very low value of cohesion, $c'\simeq 1$ psi (6.6 kPa), would do away with these inconvenient circles without significantly affecting the analysis results. Both $c'= 0$ and $c'= 1$ psi (6.6 kPa) will be used in conjuncture with the true curved envelope to determine the extent of variations of applicability and the factor of safety values caused by the modification of the cohesion intercept.

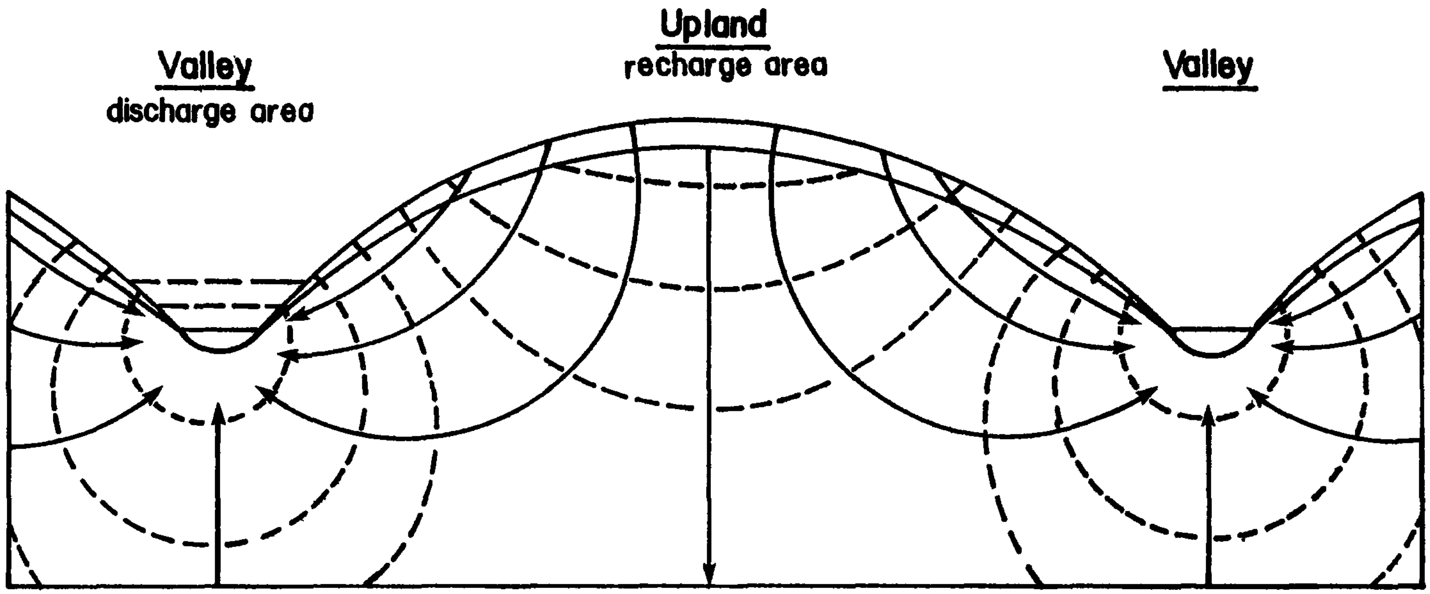
5.5 Groundwater Conditions

The flow of groundwater in a porous medium has been intensively studied from the hydrogeological standpoint in the past, though these analysis were mainly concerned with quantitative evaluations for the development of confined aquifers and/or the determination of the hydrologic budget.

Hubbert, in 1940, proposed a more generally applicable flow model in which the direction of groundwater motion in any saturated water bearing medium is controlled by differences in the hydraulic rather than the pressure gradient. The difference in potential energy causes a displacement of the groundwater towards the area of weakest hydraulic charge. The resulting groundwater model shown in Figure 5.8, assumes the following:

- the water is incompressible and has a uniform density and viscosity,
- the flow regime is permanent (constant limiting conditions),
- surface infiltration is the only source of recharge, and discharge takes place through the river channel,
- and the porous medium through which the groundwater flows is saturated, homogeneous and isotropic.

The infiltrating surface waters define an horizon where the pore pressure is equal to the atmospheric pressure,



GWT = groundwater table

(After Hubbert, 1940)

Figure 5.8

SIMPLIFIED REGIONAL FLOW SYSTEM IN UNIFORMLY PERMEABLE MATERIALS i.e. where the effective height of the water column is zero. This piezometric surface is not the groundwater phreatic surface normally considered but the interface between capillarity controlled flow in unsaturated conditions above and permeability and hydraulic gradient controls below.

For the conditions implied in the above model, the flow direction is generally downward in the highlands or recharge zone, while this trend is reversed to an upward flow below the base of the slope in the lower discharge area. This results in non-uniform porewater pressure distributions in areas of topographical variations. This type of non-hydrostatic flow regime seems to correspond to what is generally observed near slopes (Patton, 1974), and more specifically in the Champlain Sea clays (Fletcher, 1971; Scott, 1971; Scott et al, 1973 and 1976, Drouin, 1975; Lafleur, 1978; Fransham, 1978) where the difference between the actual groundwater flow and hydrostatic porewater pressure distribution is accentuated by the presence of low permeability soils. In some of these areas, further variations in hydraulic gradient are caused by the presence of more pervious layers near the base of the slope.

Classical effective stress slope stability analyses mainly rely on ratios of the hydrostatic porewater pressure distribution to evaluate the effect of groundwater flow in a slope. Porewater pressures can be evaluated from the height of the water column (piezometric surface) by an expression of the form:

$$u = \gamma_w * h_w * \alpha$$

where u is the porewater pressure,

γ_w, the unit weigth of water,

h_w, the height of the water column, and

α, a coefficient of proportionality between the true water column height and its effective height(usually varies between one, for hydrostatic conditions, to the squared cosine of the piezometric surface slope for parallel to groundwater surface flow),

or for total stress by an expression of the form:

$$u = r_u * \gamma * h$$

where γ is the unit soil weigth,

h, the height of the soil column and

r_u, a coefficient of proportionality between the effective porewater pressure and the total stress (defined as $\bar{B}$, Bishop, 1955).

In both of the above methods of determining porewater pressures, a constant coefficient describes a uniform groundwater distribution and flow direction. The flow direction is considered to be either horizontal or subparallel to the determined groundwater table, and hydrostatic conditions are assumed at the top and toe of the slope (Figures 5.9 and 5.10). The piezometric surface is then a flow line describing the upper limit of a free-water body in which there is no surface exchange either from infiltration or evaporation.

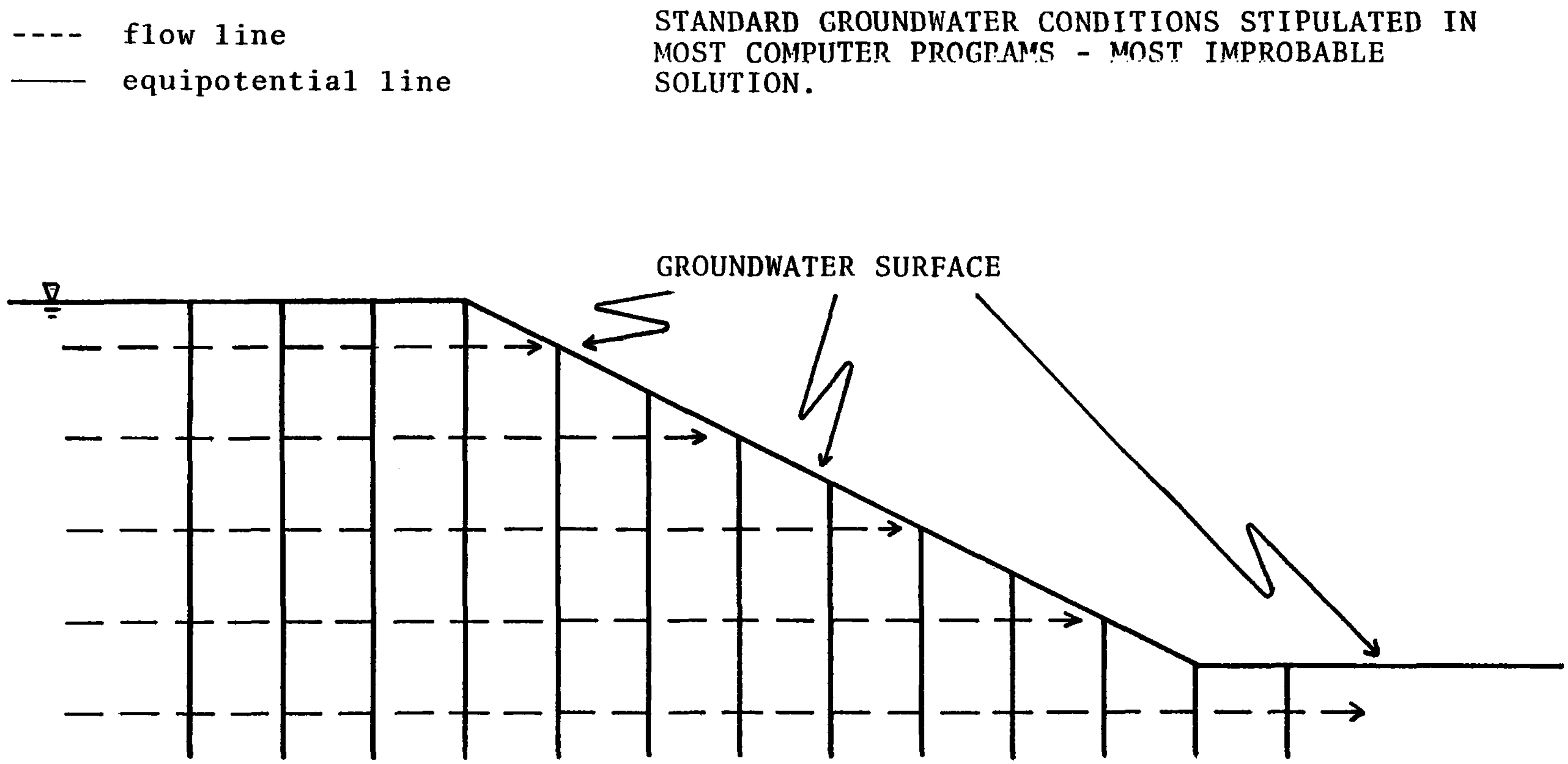


Figure 5.9 EXAMPLE OF HORIZONTAL FLOW IN SLOPE - HYDROSTATIC CONDITIONS (HORIZONTAL FLOW LINES)

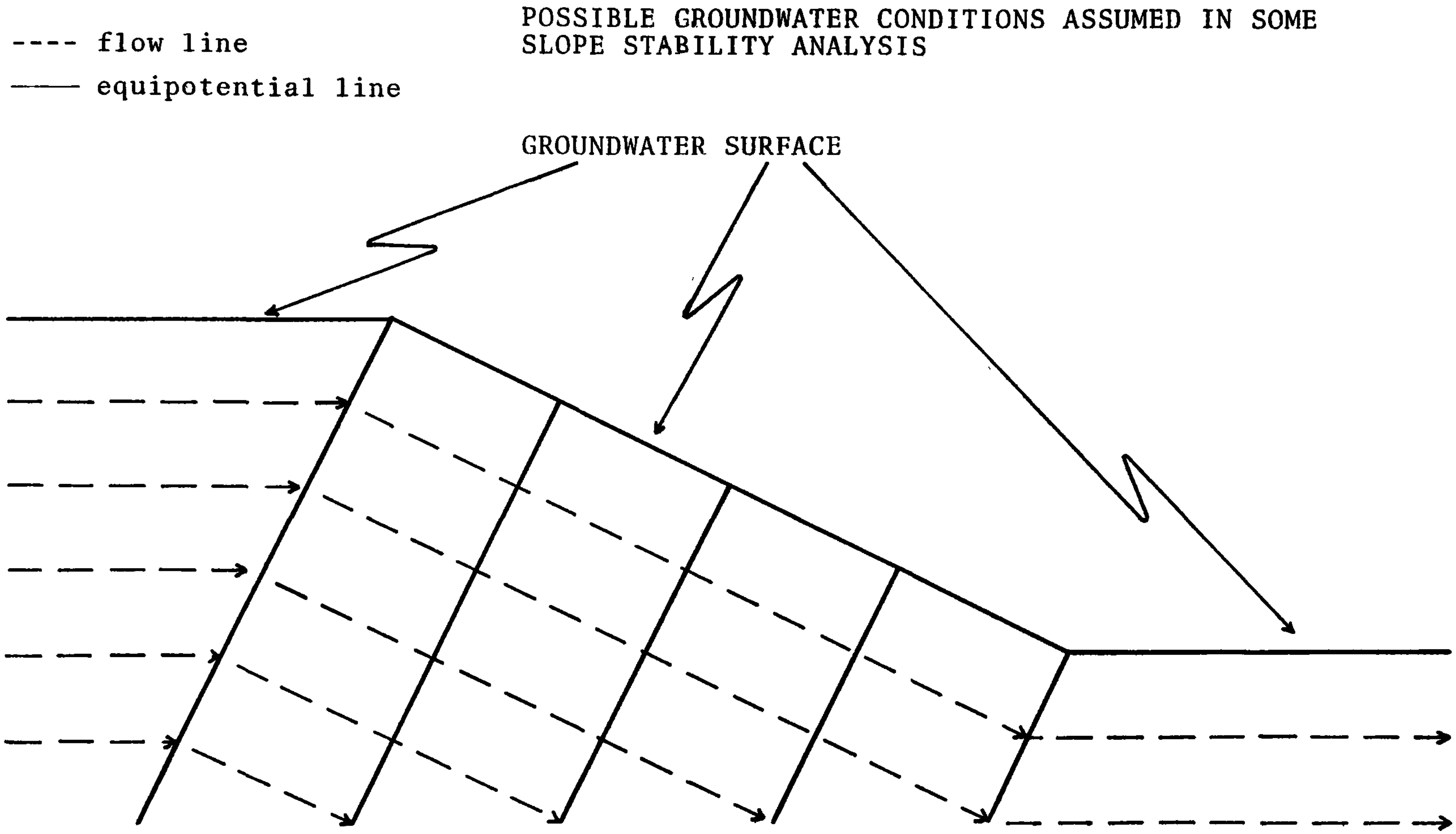


Figure 5.10 EXAMPLE OF PARALLEL FLOW IN SLOPE.

These conditions are seldom observed in nature since a constant exchange takes place between the water table and the ground surface. Furthermore, the strong vertical groundwater component measured at the base of slopes indicates quite a different flow regime than would result from the horizontal flow generated by hydrostatic conditions. At most Leda clay sites, the piezometric surface may be assumed to coincide with the limit between saturated and unsaturated states and localised at the surface in the spring when the most favourable conditions for slope instability exist due to the high infiltrations from snow melt.

From the slope stability point of view, hydrostatic conditions are often described as the worst possible groundwater state. But it is evident that a downward flow at the top of the slope with an upward flow at the toe, as illustrated in Figure 5.11, will generate a greater increase in the overturning moment and hence a decrease in the stabilizing mass, resulting in a net reduction of the factor of safety. Such a model is more critical than hydrostatic conditions and may be considerably modified in areas of regional recharge or discharge, or by permeability variations within the slope.

An homogenous slope composed of clay to infinite depth will show, under the previously discussed conditions, a flow system fairly similar to the one discussed (Figure

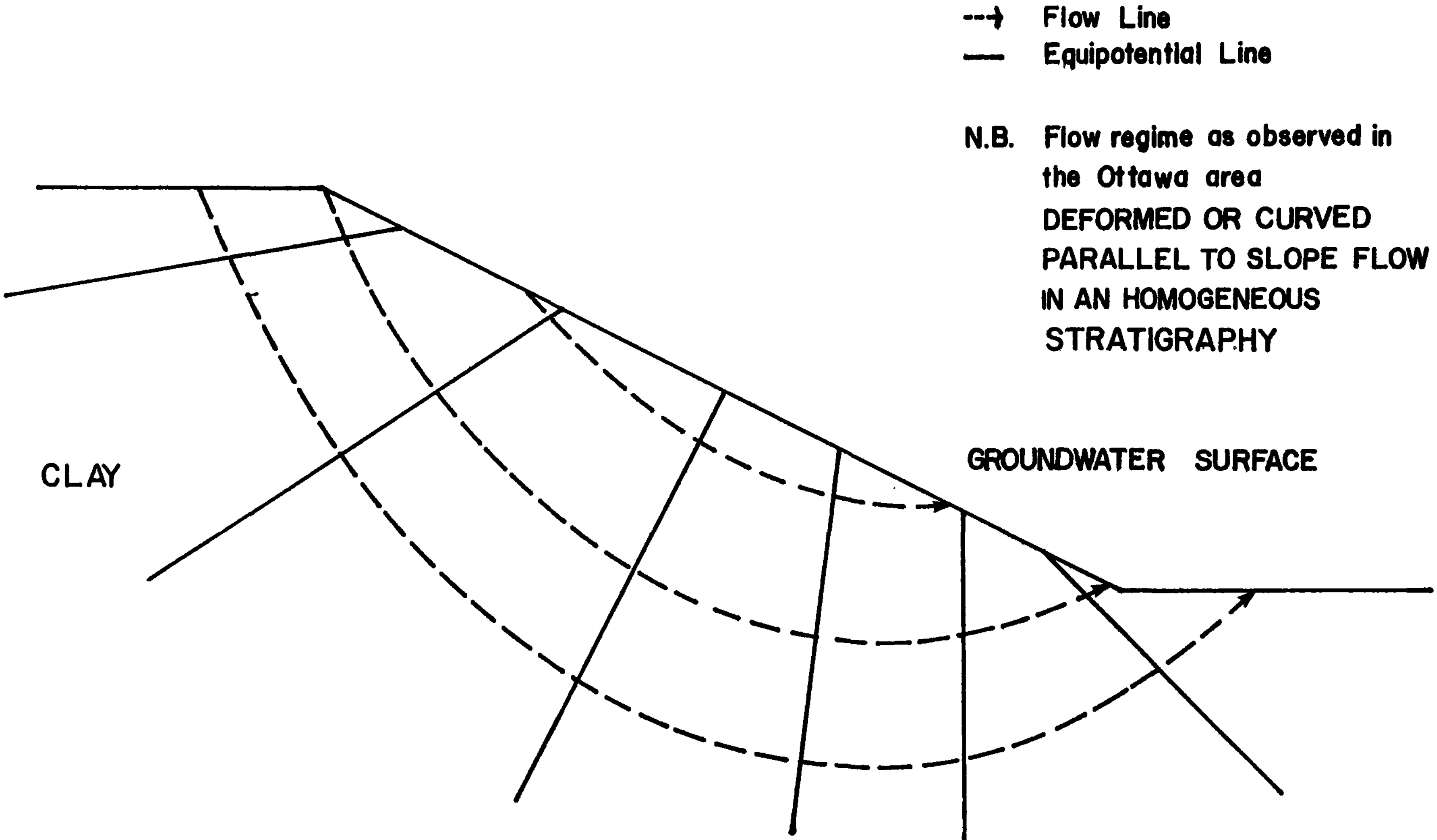


Figure 5.11 EXAMPLE OF A TRUE FLOW REGIME IN A SLOPE
-CLAY LAYER TO INFINITE DEPTH-

5.11). The presence of a more pervious horizon within the slope will considerably modify the direction of flow; gen- enerally two sets of flow conditions arise from the presence of a permeable layer at most observed sites.

If the pervious horizon outcrops at the toe of the slope, this aquifer acts as a drain and, in normal regional recharge conditions, will generate a downward flow in the overlying less pervious material, offering a lower energy channel for the groundwater (Figure 5.12). Parallel to slope groundwater flow and the permeable layer at base offer very similar flow conditions except for a slight variation of flow line at depth, though these differ considerably in that the failure circles in the stratified case are limited to levels at or above the toe of the slope because of the presumed more rigid nature of the aquifer zone.

If the permeable horizon is below the toe of the slope and does not outcrop in the vicinity, this pervious layer acts as a drain for the clay further into the slope while it is itself drained through the overlying impervious material at the toe of the slope. This condition explains the strong artesian pressures measured at many sites in the Ottawa area and usually accompanied by a regional recharge of the aquifer (Figure 5.13).

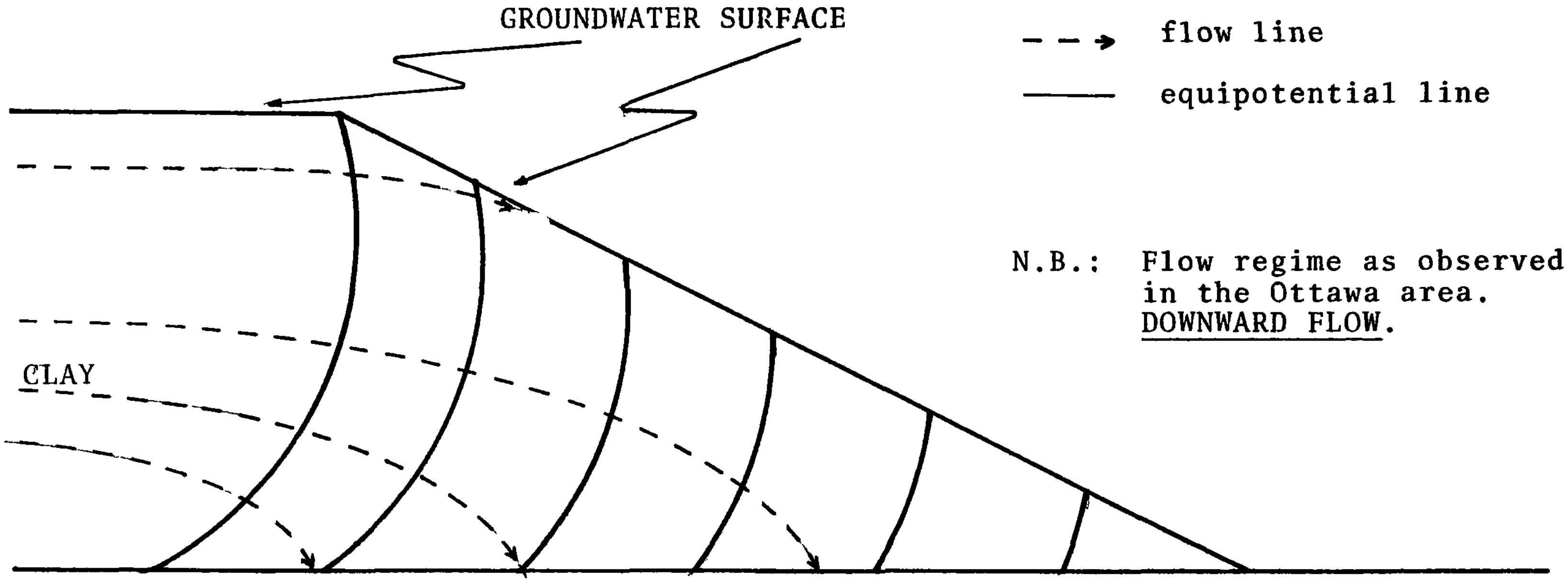


Figure 5.12 EXAMPLE OF A TRUE FLOW REGIME IN A SLOPE
- PERMEABLE LAYER AT BASE OF SLOPE -

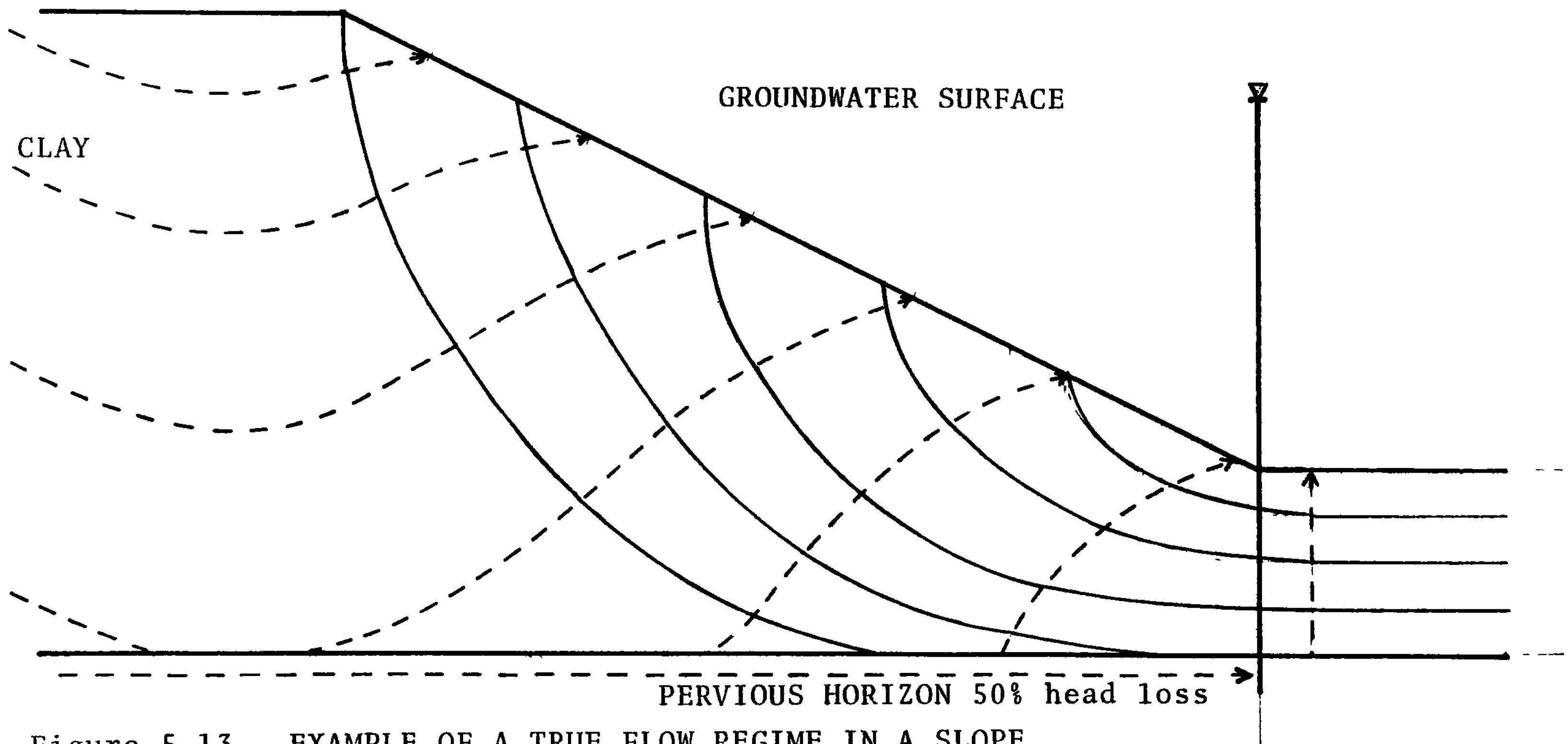


Figure 5.13 EXAMPLE OF A TRUE FLOW REGIME IN A SLOPE
- PERMEABLE LAYER BELOW BASE OF SLOPE -

The above discussion has indicated five possible groundwater flow types which will be analysed in the present study and are summarised below:

- hydrostatic or horizontal flow,
- parallel to ground surface flow,
- true flow in a homogeneous material,
- downward flow drained by a pervious horizon outcroping at the base of the slope, and
- artesian upward flow at the base of a slope.

Figues 5.9 to 5.13 illustrate these conditions.

The comparison of the results of the analysis done with these five flow types will permit to evaluate the amount of the variation in the factor of safety that can be expected between true flow conditions inferred from actual groundwater observations and the uniform flow assumed in classical geotechnical analysis. This comparative analysis will give an indication on the precision required in estimating stratigraphy and porewater pressure distributions.

A comparative analysis considering variations of:

- slope height with a fixed gradient,
- soil shear strength,
- stratigraphic limits and
- porewater pressure distributions

will give an indication of the relative importance and influence of these factors in slope stability analysis and permit to evaluate the degree of precision required in determining these principal parameters.

CHAPTER 6

THE COMPUTER PROGRAM

6.1 General

The program used in this study was developed in response to needs expressed by various consultants and researchers of the Ottawa area in having a simple efficient slope stability analysis tool adapted to the type of investigation required for the Eastern Canada Champlain Sea clays. This program evolved from the use of program SSBM, ancestor to LEASE of the ICES package, and from other available computerized slope stability analysis methods by the author in the 1974-1975 period at the University of Ottawa.

As discussed in the previous chapter, this program offers a computerized Bishop modified method of analysis taking into account the groundwater flow conditions and the soil's shear behaviour as expressed by the results of the field piezometric observations and the laboratory testing program. None of the other programs presently known have facilities to handle both factual groundwater flow nets and curved Mohr-Coulomb rupture envelopes.

This chapter reviews some of the aspects of the known computer programs dealing with the Bishop modified method of analysis. A comprehensive description of the program facilities will also be given. Two program versions, adapted to the type of available hardware, are offered:

- a Fortran program edited on H level for the University of Ottawa IBM 360/365
- and a second more limited version using a Texas Instrument TI-59 programmable mini-calculator.

Though the program was extensively tested and was found to give mathematically exact solutions, the author assumes no responsability for errors that may occur from the use of the present programs.

6.2 Review of Some Bishop Analysis Programs

Many computer programs using the Bishop modified method of analysis have been proposed in the past. Of these, four packages are presently available in the Ottawa area for research or commercial applications:

- SSBM, whose exact origin is not known, is a poorly documented program. Many difficulties are encountered in normal runs mainly because of either negative arguments which generate imaginary numbers (square root of a negative value), or divisions by zero (infinite value). The program handles porewater pressure through a single or multiple piezometric surfaces combined with $\bar{B}$ and u_o soil parameters; the explanations on the use of the groundwater facilities are obscure. The program listing and deck is available at the department of Civil Engineering of the University of Ottawa.

- LEASE-1 (Limit Equilibrum Analysis for Soil Engineering), presented by Bailey and Christian (1969), is part of the ICES package (Integrated Civil Engineering System) developed at the Massachusetts Institute of Technology. Both Fellenius and Bishop analyses are done by this program. Porewater pressure are computed from a single or multi-piezometric surfaces system or from the soil's r_u factor. Though the ICES package is available at the University of Ottawa, the LEASE program was not purchased with the package and is not on line on the University computer. The use of this program is commercially available through the services of Systems Dimensions Limited, Ottawa; because of its commercial nature, the program is stored in binary machine language, and listings are unobtainable.

- SLOPE, developed by Fredlund (1974), is by far in many opinions the best stability computer package yet offered for both commercial and research purposes. It is well documented and illustrated, and presents a comprehensive sequence of user options. Fellenius, Bishop, Spencer, Janbu and Morgenstern-Price methods can all be done using this program; output can be controlled and plotter facilities are available. Groundwater flow influence is calculated from a single or multi-phreatic surfaces system, from the soil's r_u factor, or from a grid distribution of equipotential pressure points. The program requires a considerable amount of machine space, and only few of the options offered are usually used in a typical analysis. The program is well suited for research purposes or for large parametric or comparative studies; its necessary link to the large computers may inevitably limit its use for the smaller consulting services who only have limited access to these machines.

- MBSB, published by Bowles (1974), is inoperative and was modified by St-Louis (1978) to run on the University IBM 360/365. The program computes porewater pressures from a single piezometric line, hydrostatic conditions or from an average r_u factor for the whole slope. The documentation is poorly developed and the program seems to offer no manipulation advantage over its predecessors. The program is very short and may possible be adapted to smaller computers, though no indications for this procedure are given. As in SSBM, certain conditions will not be properly analysed due to simplifications which are incorporated in the programming logic.

The limiting factor for the industrial application of most computer programs used by the author lies in the uncertainty in both the method of use and in the representation of the results given by the method. The main cause of such difficulties can usually be related to a poor adaptation of the input mechanisms to the type of problem analysed and to the engineer user's background, as well as to an unsatisfactory documentation of the program. The unavailability of listings for the better commercial versions further handicaps the user since he cannot verify the programming logic nor modify the program for a specific problem. Because of these unknowns, computer programs are often related to a mysterious "black box", the use of which may set the practising engineer in a very uncomfortable position since he is solely responsible for the interpretation and the results obtained from the computer analysis. Errors due to either programmer or user misconceptions are always possible, and cannot be verified with poorly documented programs. A comprehensive documentation may help demistify computer programs and generate a more efficient use of these tools.

6.3 Program Requirements

The most obvious requirement of a program is the desired method of analysis. Less evident characteristics, such as documentation standards, error checks, simplicity of programming and adaptability of the program, are often considered secondary and are sometimes sacrificed. The importance of these factors is greatly underestimated since these mainly influence the ease of use of a computer program.

Basic documentation requirements for engineering computer programs have been discussed by the Committee on Computer Applications of the Geotechnical Engineering Division of the American Society of Civil Engineering (1973). Their report stresses the necessity of a comprehensive user oriented documentation and recommends the use of a universal scientific programming language, such as Fortran IV. A technical file format (Figure 6.1) is also suggested to identify a program and its main characteristics.

The type of comprehensive documentation generally needed for any engineering application program can be divided into four levels:

1o a theoritical treatment of the program in which the mathematical and engineering solutions are discussed to help the user decide if the program is compatible with the type of solution sought; expected input and significance of output are explained. This description of the program should be complemented by:

2o a set of typed examples illustrating the characteristics and facilities of the program; method of data preparation, options, input format and output type.

3o Programmed controls and messages to inform on the internal option procedures or assumptions and to control program default if encountered. Machine interruptions of a run

Figure 6.1 PROGRAM IDENTIFICATION

1. Program Title:

   Slope stability analysis by the Bishop modified method using an equal pressure net and non-uniform shear properties.

2. Program Code Name:

   SIOU, slope investigation Ottawa university

3. Writer:

   G. Deschamps

4. Organisation:

   Department of Civil Engineering, University of Ottawa

5. Date:

   May, 1978

6. Updates, versions:

   No updates, two versions; Fortran for IBM 360 and TI - 59 mini-calculator

7. Abstract:

   The program will analyse set failure circles by the Bishop modified method of slices considering groud-water flow represented by an equal pressure net and non-uniform soil shear strength parameters.

occur when errors are encountered during the processing of a program; such errors are normally caused by mistakes in the input data set or in the program logic. These controls should allow for a normal program termination or correction of the more obvious errors before machine interruption occurs. The messages should sufficiently explain the source and possible cause of the problem encountered. The programmer should not rely on compiler messages because most users are normally not sufficiently familiar with either the program itself or the programming to easily understand the source and remidy to the problem encountered.

4o A detailed program breakdown describing the mathematical solutions, computational procedures and assumptions used, to permit debugging or modifications for updating or adapting purposes. This type of detailed description of the program construction should be completed by labels in the program itself to localize and identify the various steps in each procedure.

The above described detailed documentation should give a program the flexibility needed for a comprehensive use.

Slope stability computer applications offer a further point of consideration by the variability in size and type of problems analysed as well as by the accessibility to the machines and time required for data preparation.

The use of large computer facilities may be economical for extensive parametric studies, but for short analyses the time required to prepare the data in the necessary format (card punching) and execute the runs on machines to which the consulting engineer has only limited access may prove to be an expensive enterprise.

Since most routine analyses are only concerned with a specific set of limiting conditions and since programmable mini-calculators are readily and inexpensively available to most consultants today, a program adapted to these analytical tools would permit the in-house analysis of slope stability problems. This would eliminate travelling time between office and computing centre and also the need of punching the information on cards.

The design of a slope stability program adapted to mini-calculators requires a smaller, more limited program than those normally available on line on the large computer systems where the storage space allocated to a program is not usually a major setback. A smaller more specialized program would also permit lower running costs on larger systems, although this is not usually an important aspect because of the large difference in cost between a computer run and the engineer's time. A smaller program will increase the class rating of the job on time sharing systems allowing for a faster turnover in jobs. This is particularly important at the university teaching level were the students can learn to familiarize themselves with such techniques, not only on large systems but also on the more compact machines.

Most of the examined programs for which a listing was available used assumptions in their mathematical solutions which tend to reduce the precision of the method under certain conditions. These simplifications, such as those introduced mainly in the estimate of the punctual porewater pressure, the length of the arc of the base of the slice and the shear strength, are normally derived from generalizations made to expedite the hand solutions and are not conceived to handle extreme cases. Programs designed for use on the larger computers should be sufficiently general to handle all conceivable conditions, or otherwise specify the limits of the method of analysis.

More specifically for analysis in the Champlain Sea clays, a comprehensive slope stability analysis computer technique should take into account, as previously mentioned, the groundwater conditions inferred from actual piezometric observations or geological evidence, as represented by a flow net. The soil's shear behaviour is defined by the stress-strength envelope representing the failure criteria for the material.

All of the reviewed programs, except SLOPE, use one of two methods to estimate the punctual porewater pressure acting on the base of a slice: an effective stress ratio (r_u or $\bar{B}$) and a piezometric surface system. As previously discussed, the direct use of these methods can only evaluate the effect of uniform groundwater flow conditions.

Non-uniform flows may be handled by the use of a mean piezometric surface or r_u value as recommended by Bishop and Morgenstern (1960). This method allows only a gross approximation of the existing conditions since the piezometric distribution affects the position of the most critical failure surface and the true porewater pressures acting along the failure arc will inevitably differ from those assumed. Bishop and Morgenstern estimated a maximum error of about 7% resulting from the use of a mean value.

The combined use of different porewater pressure coefficients and/or different piezometric surfaces for various materials in an artificial stratigraphic distribution can give a more precise approximation of irregular groundwater flow conditions. This method divides the overall non-uniform porewater pressure distribution into spacial units of average uniform groundwater state, and approaches a hand finite technique.

A hand interation method may also be used to evaluate non-uniform distributions. This technique calls for successively determining the exact limiting conditions for a localized critical circle, and recalculating the new critical failure surface defined by the set of limits applicable to the previously determined failure arc. The interative use of this method presumably localizes a series of critical failure circles more and more closely spaced until two surfaces coincide within limits.

All of the above mentioned methods call upon data manipulations and transformations which are time consuming and require a considerable amount of engineering judgment and knowledge. They furthermore tend to deemphasize the true conditions existing at the site and may cause interpretation errors.

The SLOPE program offers additional facilities to evaluate the effect of groundwater from an input grid distribution of porewater pressures. Though this method can deal directly with true subsurface water conditions and does away with most data transformation, the preparation of the porewater pressure grid still requires a considerable amount of time.

A more efficient method of representing any groundwater flow type is given by the use of a flow net; this is the universal method used in representing porewater pressure distribution in slopes. In a computer analysis, a flow net can be determined by a series of equipotential or equal pressure lines, and by a single piezometric or groundwater surface flow line. The equivalent water level measured by a piezometer situated anywhere on an equipotential is given by the intersection of this equal pressure line and the piezometric surface. Porewater pressures can thus be directly evaluated by linear extrapolation between equipotential lines, and the piezometric surface determines the limits of the saturated zone. Since lines are used to define the flow net, the method of input is identical to the one used to define the slope and subsoil geometry, and practically no data manipulation is required to use flow nets inferred from piezometric observations.

A similar discussion to the one above may be given for the representation of the effect of non-uniform soil shear strength.

6.4 Factor of Safety Distribution

The approximate lowest factor of safety value for a given set of conditions may usually be localized by running a trend analysis on the results obtained from a series of trial failure surfaces. This type of analysis can usually be incorporated in the computer program (search facility) or, more usually, is a visual scan of the factors of safety preferably presented on a grid format according to the coordinates of the failure circle centre and radius. Examples of factor of safety grid distributions, as given by the present Fortran version, are shown on figure 6.2.

Idealy, a grid distribution of factors of safety shows a near exponential spatial distribution similar to the models used to describe gravitional fields; the locus of such a distribution is occupied by the lowest factor of safety value. Such distributions are normally thought of being composed of a single locus, though in fact local "lows" may be observed due to non-uniformities in the geometry or parameter distribution: this is particularly noteworthy with multi-layered stratigraphies or irregular soil shear properties. Such distributions, though showing a general tendency toward a lowest value, are specled by secondary local low values. Because of the limited spacial extent of the influence of these local low values, the probability of encountering such values in an analysis is greatly increased with closely spaced failure circle centers.

As previously mentioned, the use of c' = 0 in a slope stability analysis generates lowest factors of safety for extremely shallow failure circles which are presumed to be non-representative of the engineering behaviour of slopes. The resulting factor of safety grid distribution shows a linear trough of values on the in-slope side of the limit of the failure arc intersections with the slope surface which

a) with c' = 0 (two loci)

TANGENTIAL LEVEL: 110.0

/	500.0	520.0	540.0	560.0	580.0	600.0	620.0	640.0	660.0
340.0 /	2.37	1.91	1.63	1.46	1.37	1.30	1.23	1.05	0.UT
320.0 /	2.34	1.87	1.59	1.42	1.34	1.26	1.17	1.04	0.UT
300.0 /	2.31	1.82	1.53	1.38	1.30	1.22	1.12	0.UT	0.UT
280.0 /	2.28	1.78	1.49	1.33	1.26	1.17	1.08	0.UT	0.UT
260.0 /	2.26	1.73	1.44	1.30	1.24	1.12	1.07	0.UT	0.UT
240.0 /	2.26	1.70	1.39	1.26	1.17	1.12	1.06	0.UT	0.UT
220.0 /	2.26	1.65	1.36	1.24	1.13	1.17	0.76	0.UT	0.UT
200.0 /	2.30	1.61	1.32	1.21	1.15	1.19	0.UT	0.UT	0.UT
180.0 /	2.42	1.60	1.29	1.20	1.20	1.14	0.UT	0.UT	0.UT
/	500.0	520.0	540.0	560.0	580.0	600.0	620.0	640.0	660.0

b) with c' = 1 p.s.i. (one locus)

TANGENTIAL LEVEL: 110.0

/	500.0	520.0	540.0	560.0	580.0	600.0	620.0	640.0	660.0
340.0 /	2.37	1.93	1.65	1.49	1.40	1.35	1.34	4.22	0.UT
320.0 /	2.34	1.88	1.61	1.45	1.37	1.30	1.37	35.76	0.UT
300.0 /	2.31	1.83	1.56	1.40	1.33	1.27	1.54	0.UT	0.UT
280.0 /	2.28	1.79	1.50	1.36	1.29	1.23	1.83	0.UT	0.UT
260.0 /	2.26	1.74	1.45	1.31	1.26	1.21	2.36	0.UT	0.UT
240.0 /	2.26	1.71	1.40	1.27	1.19	1.28	3.70	0.UT	0.UT
220.0 /	2.26	1.66	1.37	1.25	1.16	1.39	13.60	0.UT	0.UT
200.0 /	2.30	1.62	1.33	1.22	1.21	1.55	0.UT	0.UT	0.UT
180.0 /	2.42	1.61	1.31	1.22	1.28	1.84	0.UT	0.UT	0.UT
/	500.0	520.0	540.0	560.0	580.0	600.0	620.0	640.0	660.0

Figure 6.2 EXAMPLES OF FACTOR OF SAFETY GRID DISTRIBUTION

tends to mask the more realistic low factors of safety in a trend analysis.

Fredlund (1974) proposes a mechanism to remove the extremely shallow failure surfaces generated by a cohesionless analysis by which all failure wedges not having a minimum thickness are ignored by the computer program. The suggested technique does not resolve the influence of these shallow slices which may extend considerably beyond the immediate surface area of the slope: any trend analysis on a uniform failure circle grid of this type will still indicate a lowest value at the allowed intersection limit of failure arcs and the slope boundary, unless a local low has a value less than the factor of safety at the intersection limit.

Since the use of a computerized search procedure, or of any trend analysis method which cannot take into consideration the overall factor of safety data set, may lead to erroneous results, a summary of results represented by a grid distribution of factors of safety is judged preferable to manualy evaluate the most critical safety factor value.

6.5 Method of Analysis

The program calculates the factors of safety according to the Bishop method of analysis for a series of failure arcs passing through a specified slope geometry by the method of slices. Ten slices are used per soil layer encountered by the failure arc below the soil surface. Since the method assumes the failure surface to be approximated by a circular arc, the factor of safety is evaluated as the ratio of stabilizing moments to the sum of all overturning moments. The resisting moments are derived from the available shear strength mobilized along the assumed rupture surface; the factor of safety is then the coefficient by which the total shear strength must be reduced so that the analysed mass is in a state where counteracting moments are equal (limit equilibrium).

In order to do a complete analysis, the program requires the following input:

1o the slope surface and subsoil geometry describing the extent of the material within the slope,

2o the geometry of piezometric surface

3o the geometry of equipotential lines

4o the unit weights and shear strength properties of the soil types of the slope, and

5o the location of the circular failure surfaces to be analysed.

Through the use of the various input facilities, the program will perform an analysis considering the following:

1o total or effective stresses,

2o linear (constant c' and ϕ') or curved soil failure envelopes, 3o hydrostatic, uniform and non-uniform porewater pressure distribution, and

4o submerged or partially submerged slopes.

Both the International and Imperial system of units may be used to define a problem, by the use of the proper input facilities.

6.6 Data Preparation

The method for describing the problem to be analysed is similar to the technique used in the standard hand analysis. The cross-section geometry representing the site is plotted on a normal rectangular grid using a series of straight lines to approximate the slope surface and subsurface boundaries between materials of different properties. The piezometric surface, which includes free-water bodies, and the equipotential lines are plotted in an identical fashion. The lines defining the slope geometry describe the upper limit of soil types; air and water need not be considered as soils in the present program.

No vertical lines (infinite slope) should be used to describe any of the geometry because they do not allow any solution of the general linear equation of the form:

$$y = m \cdot x + b$$

Vertical lines may be represented by near vertical lines; the slope of a line should never exceed 100. The extent of the geometry should also be long enough to cover all examined failure circles.

The end coordinates of each segment defining the geometry are established from an arbitrary origin and are used to describe the input geometry data. The use of negative values for the coordinates is proscribed. The whole geometry should be defined in a single quadrant; quadrant I and IV usually correspond to the data obtained from land surveying. Either right or left facing slopes may be described. Figure 6.3 illustrates the description of a typical problem by the recommended method; the resulting numerical data is indicated as coordinates on the cross-section; since the program extrapolates between lines and points, the data density should be sufficient to account for all irregular variations.

If no piezometric surface is defined, the program will execute a total stress analysis. For total stress calculations in an effective stress analysis, the piezometric surface defines the upper limit of the saturated zone; if the saturated-unsaturated limit does not correspond to the piezometric surface, the use of an artificial soil layer having a moist unit weight equal to the true soil's saturated weight will allow for the correct solution. Freewater bodies, such as ponds or rivers, need only be defined by the piezometric lines above the soil surface; submergence and partial submergence are also described by the position of the piezome-

—— slope or soil boundary

—— piezometric surface

---- equipotential line

(0,200) X and Y values of a point coordinate

SOIL PROPERTIES

	γw	γw	c'	φ'
SAND	110	120	0	35°
CLAY	100	100	as described below	
TILL	110	110	100	30°

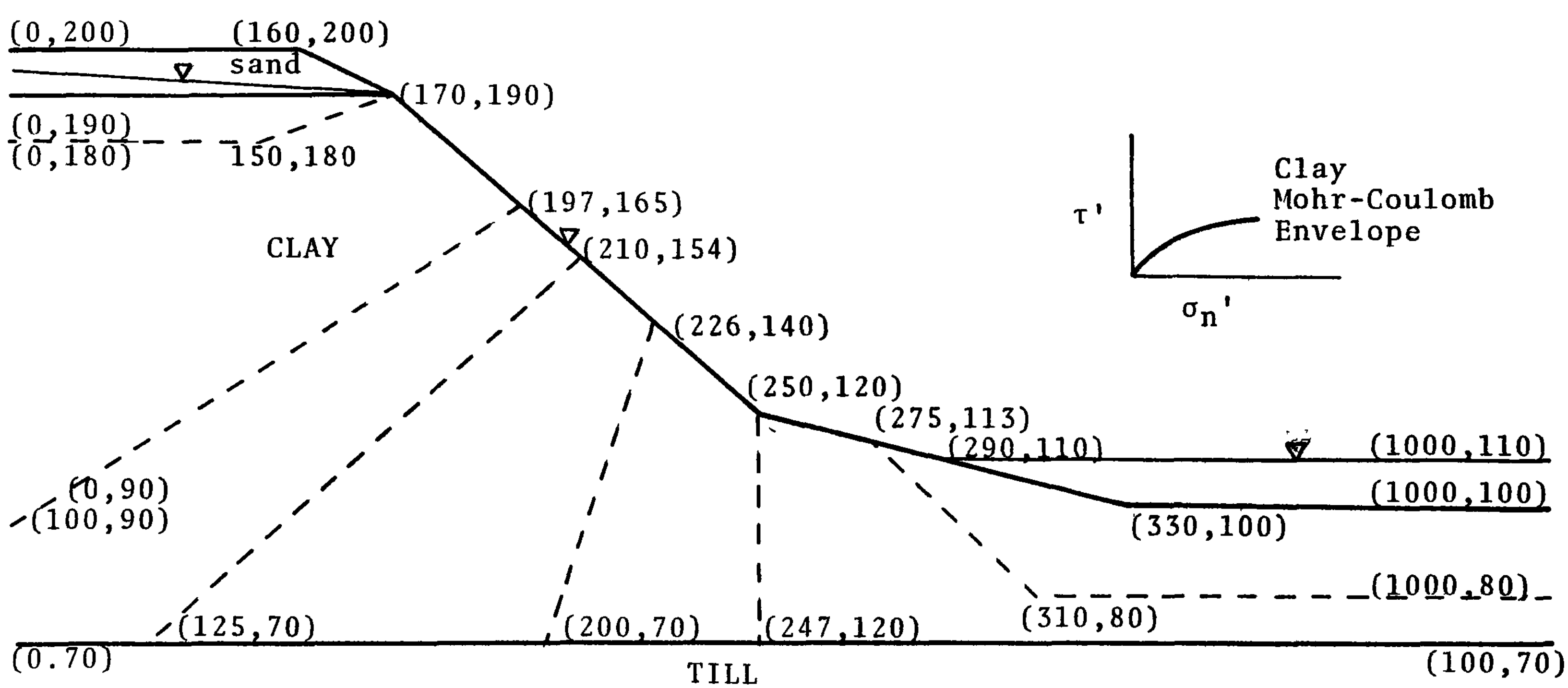


Figure 6.3 DESCRIPTION OF TYPICAL PROBLEM

tric surface. Since only one groundwater surface can be defined, the effect of an isolated perched water table can only be approximated through the use of artificial soil types.

The porewater pressure distribution is described by a series of equal pressure lines. The porewater pressure acting at the center of the base of a slice is determined by linear extrapolation between the two failure circle-equipotential line intersections on each side of the slope; if only one equal pressure line is cut by the failure surface, or if the base of the slice is situated between an equipotential line and the piezometric surface, the program evaluates the porewater pressure by assuming an equipotential line passing through the center of the base of the slice and parallel to the first equal pressure line encountered. If no equipotentials are encountered by the failure circle below the piezometric surface, the program assumes hydrostatic conditions. Since no vertical lines may be used in defining any of the geometry, vertical equipotential lines may be represented by near vertical lines in the flow net (see restrictions mentioned above). The present analysis contains no hydrodynamic considerations.

The soil properties used in the analysis are the moist and saturated unit weights, as well as the effective normal stress-effective shear strength envelope approximated by a series of straight lines. The unit weights should be defined in pounds per cubic foot (Imperial system) or kilograms per cubic meter (International system). The stress-strength relationship is defined by the coordinates of the points defining the lines representing the envelope. The first point is given by the shear strength (τ') value at an effective normal stress (σ_n') of zero (cohesion or cohesive intercept). All the other points are defined by $\sigma_n' \cdot \tau'$ combinations describing the end-coordinates of the segments and their range of applicability; the last line defined is assumed to have an infinite extent with increasing values. The use of a single line to describe the soil's shear properties defines the standard constant cohesion (c') and the internal angle of friction (ϕ) soil parameters used in classical geotechnical engineering.

The circular failure surface is defined by the coordinates of the center of the circle and by the level to which the circle is tangent. Fissures and loads may be taken into account by the proper use of geometry and artificial soil types.

The present suggested program and procedure can define and analyse most any set of conditions usually examined by the Bishop modified method of analysis. Its main advantages lie in its flexibility in handling non-uniform porewater pressure distributions and soil shear strengths.

6.7 Program Infrastructure

The program is composed of a series of steps which constitute the programming or mathematical procedures leading to the required problem solution. Though the two program versions differ slightly due to machine capacity, these steps approximately correspond to the subroutine flow in the Fortran and TI-59 versions. The basic program infrastructure is illustrated in Figure 6.4 by a schematic flowchart. The analytical geometry used to develop the mathematical solutions in each of the steps is described in detail in Appendix A.

The construction of the program is essentially identical to the method used in the hand solution. The basic steps defining the program procedure are given below.

1o The basic slope, subsoil, piezometric surface and equipotential lines geometry is read into the program and stored as the coordinates of the end of linear segments.

2o The circular failure surface is represented by the coordinates of the center of the circle and by its bottom tangent level which defines the radius of the circle.

3o The slope-failure circle intersections are computed. If the failure circle does not intersect the slope, the pro-

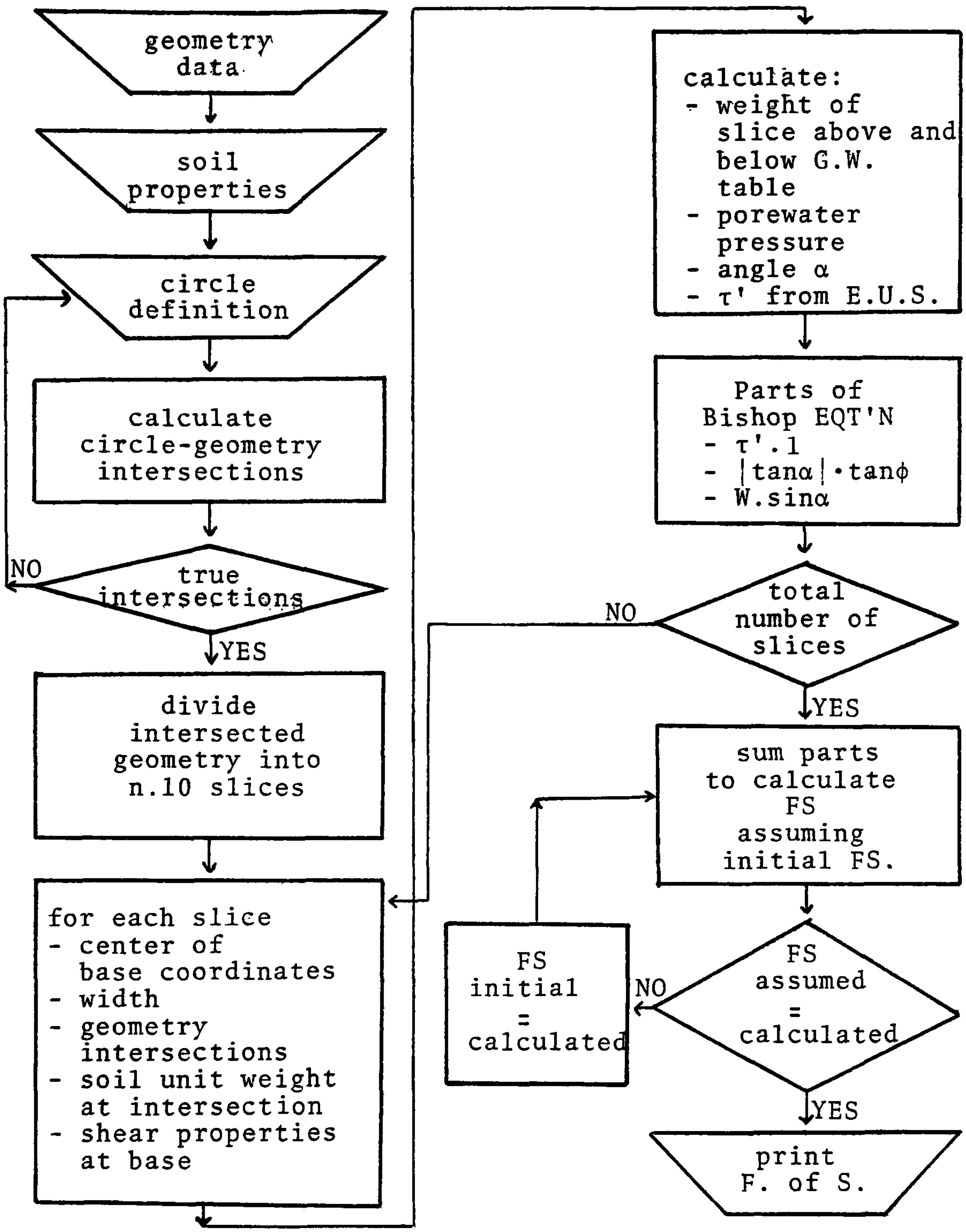


Figure 6.4 PROGRAM SCHEMATIC FLOWCHART

gram terminates and returns to step 2 to redefine a new failure surface.

If the circle intersects the slope, the relative position of the failure and equipotential surfaces is determined; if no piezometric lines are encountered by the failure arc, the program will execute a total stress analysis.

If the piezometric surface is cut by the failure arc, the circle-equipotential lines intersections are computed, the first and last being defined by the circle-piezometric surface intersections. If no equipotentials are cut by the failure arc, the effective stress analysis will assume hydrostatic conditions.

Intersections are computed from the roots of the quadratic equation which allows for the simultaneous solution of a circle and of a line.

4o The intersected slope geometry is divided into 10 slices; the slice width and the coordinates of the center of the base of each slice are computed.

5o For each slice, the center of the slice-geometry intersections and the soil properties at these intersections, including those at the base of the slice, are determined.

6o For total stress analysis, the total unit stress acting at the base of the slice is determined from the soil's moist unit weight along the total slice height. For effective stress analysis, the total unit stress at the base of the slope is estimated from the moist unit weight of the soil above the piezometric surface, and the saturated unit weight below the piezometric line. The effect of free-water bodies is estimated by adding to the total unit stress the water's unit weight over the difference between the slope's surface and the piezometric line when the latter is above the slope.

When the base of a slice is below the piezometric surface, porewater pressure is determined by linear extrapolation between the circle-equipotential intersections on each side of the center of the base of the slice. If no equal pressure lines are encountered below the piezometric surface, hydrostatic conditions (vertical equipotentials) are assumed.

7o The effective unit stress acting on the base of the slice is given by the total unit stress times cosine α (angle of the line passing through the center of the failure circle and the center of the base of the slice made with the vertical) less the unit porewater pressure. If the effective stress is less than zero, it is readjusted to zero. The effective shear strength is computed from the calculated effective unit stress and the shear strength properties of the soil at the base of the slice.

8o The parts of the Bishop equation for each slice are calculated and stored:

- part 1 →the effective shear strength X the length of the base of the slice,
- part 2 →the slope of the tangent to the stress-strength envelope at the determined effective stress (tan ϕ') X the tangent α,
- total shear stress → the effective unit stress X the slice width X sine α.

The program returns to step 5 until all slice calculations are completed.

9o The factor of safety is calculated by an interation procedure using the equation reviewed in chapter 3:

- an initial value for the factor of safety of 2.0 is assumed,
- a true factor of safety is computed by the sum of part 1/(1 - (part 2 / assumed factor of safety)) for all the slices divided by the total shear stress;
- if the computed factor of safety is not equal to within 0.005 of the assumed value, the computed value is used to recalculate a new safety factor which is retested.

At the end of the factor of safety calculations the program returns to step 2 to redefine a new failure circle.

This general breakdown of the program gives an indication of the procedures employed in developing the method of solution. These steps approximately correspond to the subroutine sequence used in the Fortran and TI-59 versions, though some differences exist between these programs because of variations on the capacity of the machines utilized. A detailed breakdown of the use, facilities and limits of each version follows, and a complete listing of the programs is given in the corresponding appendices.

6.8 The Fortran Version

The Fortran version is a much more extensive and complete program as far as user facilities are concerned due to the relatively unlimited space offered by the IBM 360/365 compared to the capacity of the Texas Instrument TI-59. In writing this version the main emphasis has been put on the normal user which is unfamiliar with programming: the program contains numerous error checks and messages which enables the user to correct input mistakes, and to be informed of unusual procedures or any abnormal functioning of the program.

The computer program is written in Fortran IV language, and it was developed for the University of Ottawa IBM 360/365. Initial debugging was done on extended Watfiv which limits the use of certain expressions. The Watfiv requirements were preserved in this version to allow the use of this compiler whenever reprogramming is necessary. To prevent unecessary recompilation of the program, normal runs were made by using an object deck compiled on Fortran-H which offers a more efficient interpretation than a G-level compilation. The program requires a storage area of 90K bites. Consistency of units requires that all data be in the Imperial (foot, pound) or the International (kilogram, meter, kilopascal) systems of units.

Due to the iteration cut-off procedure used in the program, the precision of the listed results is within ±0.01, which is considered adequate in view of the approximations used to establish the different controlling parameters.

6.8.1 Procedures Characteristics

The number of slices used for the factor of safety calculations depends on the intersected stratigraphy below the slope surface. The intersected geometry is divided into 10 slices of equal width between pairs of failure arc-geometry lines intersections. The number of slices chosen is arbitrary: ten slices per stratigraphic unit seems to offer a reasonable estimate of the conditions in uniform slopes as well as in intensely stratified deposits. The program contains no facilities enabling the user to modify the number of slices used in the analysis, although this can easily be done by in-situ program modifications.

Shallow failure circles may often define more than one failure surface, especially on irregular slopes. When the failure circle defines more than one failure surface, the program informs the user and analyses each portion of the failure arc separately.

The factor of safety evaluation procedure uses a directed iterative process by which the assumed factor of safety value is approximated by an analytical geometry procedure using two lines, one of which is determined by two groups of assumed to computed factor of safety values, and the other is defined by all the possible solutions for the factor of safety in the Bishop equation (the assumed value equal to the calculated value of the factor of safety); the intersection of these two lines approach a true solution. The iterative use of the above procedure enables a more efficient method of solution than the iterative process alone.

6.8.2 Input and Controls

Two types of controls are used to verify the input data sets in the Fortran version. A code name punched at the beginning of each data card defines the type of data on the card; the use of the wrong code, usually caused either by a punching error or the mixing of the card order, will cause a termination of the run using that data set. A "total" card should also follow each data type set; this card contains the sum of the values in each card column and is mainly a check against the mispunching of data values. A column total which is not equal to the value punched on the total card will not cause a program interruption but will only inform the user of the error encountered. Other controls check the size and number of the variables as well as the extent of the geometry. A complete list of the messages associated with each control and their diagnostic is given in Appendix D.

The input procedure for the Fortran version of the present program is summarized in Table 6.1; the input formats are indicated on this table in Fortran code.

The data defining the problem is divided into five data sets:

1- the slope surface and subsoil stratigraphy, coded "LINE",

2- the piezometric surface, coded "PIEZ",

3- the equipotential lines, coded "EQPT",

4- the soil properties, coded "SOIL", and

5- the failure circle definition cards, coded "CIRC".

The input formats and sequence for each of these data units are herein explained.

The first to be read in the data set is the TITLE card. Any sequence of alphanumerics up to 80 characters long

TABLE 6.1 STEPS IN DATA DEFINITION

n.b. symbols in parantheses refer to Fortran field format code

1. Title card (20A4) (1 card only)
2. Field definition card (1 card only)

   a) NXS → no "LINE" cards (I6)
   b) NPIEZ → no "PIEZ" cards (I5)
   c) NEQ → no "EQPT" cards (I5)
   d) NSOL → no "SOIL" cards (I5)
   e) DESC → BR or SI (2X, A2)

   Description of unit system used

3. Slope surface and subsoil description (maximum 30 cards)

   a) "LINE" → code (A4)
   b) X1(i) → X-coordinate of first point of segment i (F8.1)
   c) Y1(i) → Y-coordinate of first point of segment i (F8.1)
   d) X2(i) → X-coordinate of second point of segment i (F8.1)
   e) Y2(i) → Y-coordinate of second point of segment i (F8.1)
   f) IS(i) → Soil type below described segment (I5)

4. Total card (1 card only)

   a) "TOT" →code (A4 in first 3 columns)
   b) Sum of above columns as previously defined format (A4, 4F8.1, I5)

5. Piezometric surface description (maximum 10 cards)

   a) "PIEZ" → code (A4)
   b) XPZ1(i), YPZ1(i), XPZ2(i), YPZ2(i) — X and Y-coordinates of the two points defining each segments constituting the piezometric surface-format as in 3(4F8.1)

6. Total card (1 card only)

   As described in 4, but for piezometric data-format as in 5, (A4, 4F8.1).

TABLE 6.1 STEPS IN DATA DEFINITION

7. Equipotential Lines Description (maximum 30 cards)

a) "EQPT" → code (A4)
b) XQ1(i), YQ1(i), XQ2(i), YQ2(i) — X and Y coordinates of the two points defining each segment constituting an equipotential-format as in 3 (4F8.1).
c) ELQ(i) Equipotential level as defined by the intersection of an equipotential line and the piezometric surface on a flow net (F8.1)

8. Total card (1 card only)

As described in 4, but for equipotential data-format in 7, (A4, 5F8.1).

9. Soil Properties Description (maximum 10 cards)

a) "SOIL" → code (A4)
b) IST(i) → soil type number on 1st card as defined on "LINE" card in 3 (I2)
c) WW(i) → wet or moist density of soil (F5.1)
d) WS(i) → saturated density of soil (F5.1)
e) Co(i) → cohesion intercept of shear strength parameters or effective shear strength (τ') at an effective normal shear stress of zero (σn'=0) as established from a Mohr-Coulomb rupture envelope (F5.1)
f) SIG(1,i), TAU(1,i), SIG(2,i), TAU(2,i), SIG(3,i), TAU(3,i), SIG(4,i), TAU(4,i), SIG(5,i), TAU(5,i) —
SIG Effective normal shear stress (σn')
TAU Effective shear strength (τ')
X and Y coordinates values used to describe the Mohr-Coulomb failure envelope defining the soil's shear behaviour. Up to five segments can be used to represent a curved envelope.
For a single straight line representation (constant c' and ϕ'), the slope of the line (tanϕ') can be represented by any single combination of σn' vs τ'and Co (10F5.1).

10. Total card (1 card only)

As described in 4, but for soil properties data-format as in 9, (A4, I2, 13F5.1)

TABLE 6.1 STEPS IN DATA DEFINITION

11. Failure Circle Grid Description (maximum 5 cards)

a) "CIRC" → code (A4)

b) X1T
Y1T → X and Y-coordinates of lower left most point of grid of failure circle centers when problem defined in quadrant I (12 to 3 o'clock) - otherwise point closest to origin of system (2F8.1).

c) X2T
Y2T → X and Y coordinates of lower right most point (quadrant I) of failure circle centers grid; point farthest from origin and closest to ordinate (X) (2F8.1).

d) X3T
Y3T → X and Y-coordinates of upper left most point (quadrant I) of failure cicle centers grid; point farthest from origin and closest to abscissae (Y) (2F8.1)

e) IN12(i)→ number of points along ordinates of failure circle centers grid (I3)

f) IN13(i)→ number of points along abscissae of failure circle centers grid (I3)

g) CL(i) → Level to which failure circles are tangent - defines radius of circles (F8.1)

12. Continuation card

"NEXT" or "LAST" To indicate if new data set follows or not (A4).

(corresponding to the 80 columns of a data card) may be used to label the problem. If no title is desired, a blank card should be inserted at the beginning of the data block.

The second card of the data block is the FIELD DEFINITION card. This card defines the number of lines which describes the cross-section geometry (variable NXS, columns 1 to 5), the piezometric surface (NPIEZ, columns 6 to 10), the equipotential lines (NEQ, columns 11 to 15) and number of soil types (NSOL, columns 16 to 20); a code is also used to indicate of the problem is defined in the Imperial system of units (BR) or in the International System (SI) in columns 23 and 24. This definition of the system is required because of mass to weight tranformations necessary in the evaluation of the stresses in the International system of units. This transformation is not required in the Imperial system of unit. Because of the Fortran input formats for the above integers, the number should be punched to the right of the space reserved since empty columns to the right of a number are replaced by zeros by the computer (Example: a value of 2 in column 4 is read as 20 for the variable NXS). At least one slope surface line and one soil type are necessary to run an analysis. A maximum of 30 lines each may be used to describe the cross-sectional geometry and equipotential lines; similarly a 10 card limit is applicable to the piezometric surface and to the number of soil types defined. If NXS or NSOL are less than one, or if the above mentioned limits are exceeded, the program will print out an error message and will stop the execution of the present problem to go to the next data set. Again the size attributed to each parameter matrix is arbitrary and may be easily modified through reprogramming of the dimension and IF statements.

Following the description of the problem title and of the size of the parameters used in the analysis, the data set defines the coordinates and values describing the different data units of the problem.

First the slope surface and subsoil geometry is input on "LINE" cards. Each card defines the end coordinates of a single segment according to a X1, Y1, X2 and Y2 order. The first four columns of the data card are occupied by the code "LINE". The coordinates are then punched according to the above described scheme using a 4F8.1 format (X1, columns 5 to 12; Y1, columns 13 to 20; X2, columns 21 to 28; Y2, columns 29 to 36). The last column in each space reserved for a coordinate is automatically a decimal value unless the use of a point in the reserved field defines otherwise. The last number punched on a "LINE" card is the number of the soil type below that line; this integer is punched in columns 37 to 41 and any number between 1 and 10 may be used. A total card must follow the LINE cards; this card coded "TOT" in columns 1 to 3, sums by columns the data punched on the previous

"LINE" cards.

The piezometric surface data is then deliniated in a similar fashion to the one described above. The code "PIEZ" in punched in columns 1 to 4; X1, Y1, X2 and Y2 values are punched in columns 5 to 12, 13 to 20, 21 to 28 and 29 to 36 respectively (4F8.1 format). A total card follows the data.

The equipotential data is defined by the code "EQPT". The X1, Y1, X2 and Y2 coordinates of each segment are in columns 5 to 12, 13 to 20, 21 to 28 and 29 to 36 respectively using a 4F8.1 format. The pressure level of this line, as indicated by the elevation of its intersection with the piezometric surface on the flow net, is then also input using a F8.1 format in columns 37 to 44. A total card must follow the "EQPT" cards.

The soil properties are defined by one soil type per card. The code "SOIL" in punched in columns 1 to 4 and the soil type number (integers 1 to 10) in columns 5 and 6. The moist and saturated unit weights are input in columns 7 to 11 and 12 to 16 respectively using F5.1 formats. The cohesion or τ'-intercept of the Mohr-Coulomb rupture envelope, as well as the $\sigma_n' \cdot \tau'$ pairs of points (up to five allowed) defining the normal stress-shear strength relationship are then punched in the next 65 columns also using a

F5.1 format (last digit is a decimal unless otherwise specified by a point in the field). A total card must follow the "SOIL" cards.

The failure circles to be analysed are defined by the intersections of a grid of circle center coordinates; all the circles defined by a grid are tangent to the same level since the soil stratigraphy which ususally tends to be subhorizontal, controls the position of the most critical failure circles. The circle center grid, of any parallelogram shape, is defined by the coordinates of the three corners closest to the origin of the coordinate system used, as well as by the numbers of increments between each pair of limiting coordinates. The first pair of coordinates describes the corner closest to the origin; the second and third pair of coordinates describe the corners closest to the abscissa and the ordinate respectively. The code "CIRC" is puched on the first four columns of the card. The X1, Y1, X2, Y2, X3 and Y3 coordinates are punched in columns 5 to 12, 13 to 20, 21 to 28, 29 to 36, 37 to 44 and 45 to 52 respectively (F8.1 format). The number of increments between points 1 and 2, and between points 1 and 3 are punched as integers in columns 53 to 55 and 56 to 58 respectively. The tangent level is in columns 59 to 66 with a F8.1 format. A maximum of five "CIRC" cards may be defined and no more than 15 increments will be used between coordinates. If more than five cards or 15 increments are specified, these values are readjusted to the maximum permitted. No total should follow "CIRC" cards.

The last card in a data set indicates if another problem follows or if the present data set is the last. This is simply done by the codes "NEXT" or "LAST" in the first four columns of the last card of that data set. If a new data set is defined after the "NEXT" card, the new data set must start with the title card.

6.8.3 Output

The output consists in a listing of the geometry and soil properties as a further check of the input data. The results of the analysis are presented for all the analysed failure surfaces; they are composed of a printout of the computed factor of safety, the coordinates and level of the circle, the total shear strength acting on the failure surface and the length of the failure arc. Slice data is also printed out for the failure circle having the lowest factor of safety greater than zero. This data consists of the factor of safety, coordinates and level of the failure circle, numbers of slices in the analysis, the width of the slices and, for each slice, the length of the base, the coordinates of its center, the total unit stress and unit porewater pressure acting on its base, the resulting effective shear strength and the slope of the tangent of the Mohr-Coulomb envelope at this effective shear strength.

A summary of all computed factors of safety is also presented as final data. The factors of safety are plotted on a grid according to the coordinates of the circle centers, one grid per circle tangent level.

Example runs of problems are given in Appendix F.

6.9 The TI-59 Version

The use of the large computer facilities offers a flexible and comprehensive program capable of doing almost any analysis required. The major disadvantage in using these large systems lies in the time required for displacements to the computing center and for the preparation of the data on cards. Time sharing line connected systems, such as WILBUR and APL, reduce these inconveniences though they represent additional rental costs and the available librairies are very limited.

Mini-computers, which have lately been introduced, probably offer the best solution for most consultant office requirements. Except for hand-held use, they offer most of the advantages of mini-calculators (portability and reasonable use independant costs), and can ne as flexible and comprehensive as the large computers through the languages.

used (PL-1, BASIC, etc,) and the optional hardware which can be added to a system (printout, supplementary data banks, software reading systems, etc.). Since these machines have only lately started being commercialized, mini-computers are not yet standardized and are not as universally accepted as the mini-calculators.

Programmable software using mini-calculators cradle the hopes of most engineering users in having an efficient computer tools.The advantage presented by their immediate availability, as illustrated by their portability, small size and low cost, in only clouded by the machine type language used and their inflexible hardware dependance. Most mini-calculators can now be adapted to a small printout system, but few yet offer the possibility of adding hardware to increase the memory size. The use of magnetic card software, which is available with the better programmable machines, enables one to run more complex analyses by breaking down a program into smaller subunits, though this system does not increase the program's actual active memory space.

The use of mini-calculators requires a different programming technique than normally used in working with Fortran, since the available program and data memories limit considerably the complexity of the analysis method and the number of variables which may be analysed. On the other hand, the use of these small machines presents no time sharing or time of use dependant cost considerations. Time consuming repetètive methods can be utilized to replace the storage of control variables. This process is reversed with the larger computers since the memory is virtually of unlimited size and that programming optimization aims for a certain equilibrium between the program size and its running time. This results in the specialization of mini-calculators in doing either a simple sequence of calculations, or moderately complex general computations such as statistical analysis.

Most commercial computer programs for mini-calculators are hardware defined, in that they use a permanent electronic circuit (pre-programmed calculators) or interchangeable modules to define the sequence of operators that will execute the analysis; such programming is permanent and cannot usually be directly modified. Wiseman (1976) published a series of geotechnical software programs for a Texas Instrument SR-52. The suggested slope stability analysis programs use either the Fellenius or Bishop method; they require as input the basic data for each of five slices into which the geometry intersected by a failure arc is divided (sin α, width, height and average total unit weight of each slice). The position of the water table and shear strength parameters are keyboard inputs as required by the calculation procedure. This program is intended as a complement to the hand method of analysis since it requires the determination of the forces acting on each slice and only replaces the final factor of safety iterative calculation. It is therefore mostly useful to check a particular trial failure circle.

The present suggested program is designed to do the entire analysis from basic geometry and soil properties data by the modified Bishop method using a total of 10 slices. The program is written for a Texas Instrument TI-59 coupled to a PC-100A thermal printer, and uses its software facilities to separate the procedure sequence into a series of magnetically recorded subprograms: the "CALL" function normally executed by the "MAIN" routine in Fortran is done manually on the mini-calculator. Because of the limited program memory size, the version does not contain any error checks or messages, though its interactive use does allow for the localization and verification of the solution procedure. The program can only analyse a single set of parameters at a time; it can only presume to extend the hand analysis method and cannot by any mean replace the more extensive Fortran program for the complex analysis where a series of failure surfaces, of geometries and of soil properties must be examined.

6.9.1 Program Limits

The program divides the intersected geometry into 10 slices. Two soil types may be defined in the geometry by the use of a subsoil interface. The controls for effective stress analysis are represented by a piezometric surface which intercepts four equipotential lines. The limits for the geometry layout are:

- 7 points for the slope surface,
- 4 points for the subsoil interface,
- 5 points for the piezometric surface if it differs from the slope surface, and
- 3 points each for any of the four equipotential lines.

The failure circle is defined by its center coordinates and its radius.

The soil properties are given by the moist and saturated unit weights and by a maximum of three segments representing the stress-strength envelope (the τ'- intercept and three pairs of limiting $\sigma_n' \cdot \tau'$ values).

Failure circles defining more than one failure surface should not be used since the program contains no facilities to handle such situations.

6.9.2 Program Construction

The program is structured according to the basic procedure discussed in section 6.7. The procedure distribution in each subroutine of this version is described in Figure 6.5. A detailed annotated listing of the TI-59 program is given in Appendix E.

The program is divided into 5 main subprograms recorded on magnetic cards.

The first card reads and stores the slope surface, the subsoil, the piezometric and the equipotential lines geometries, as given by the coordinates of the end points of the linear segments approximating the slope cross-section. The program calls in by a printed message for the X and Y coordinates of the "SLOPE", "SOIL", "PIEZ", "EQPT 1", "EQPT 2", "EQPT 3" and "EQPT 4" surfaces. At the end of this subroutine, the slope geometry data which is stored in the data banks is written on a magnetic card. The reading of this card re-initializes the slope geometry into the data memory banks for subsequent runs using the same basic geometry. The machine also calls for the second part of the program. Both the writing and reading procedures are called by messages.

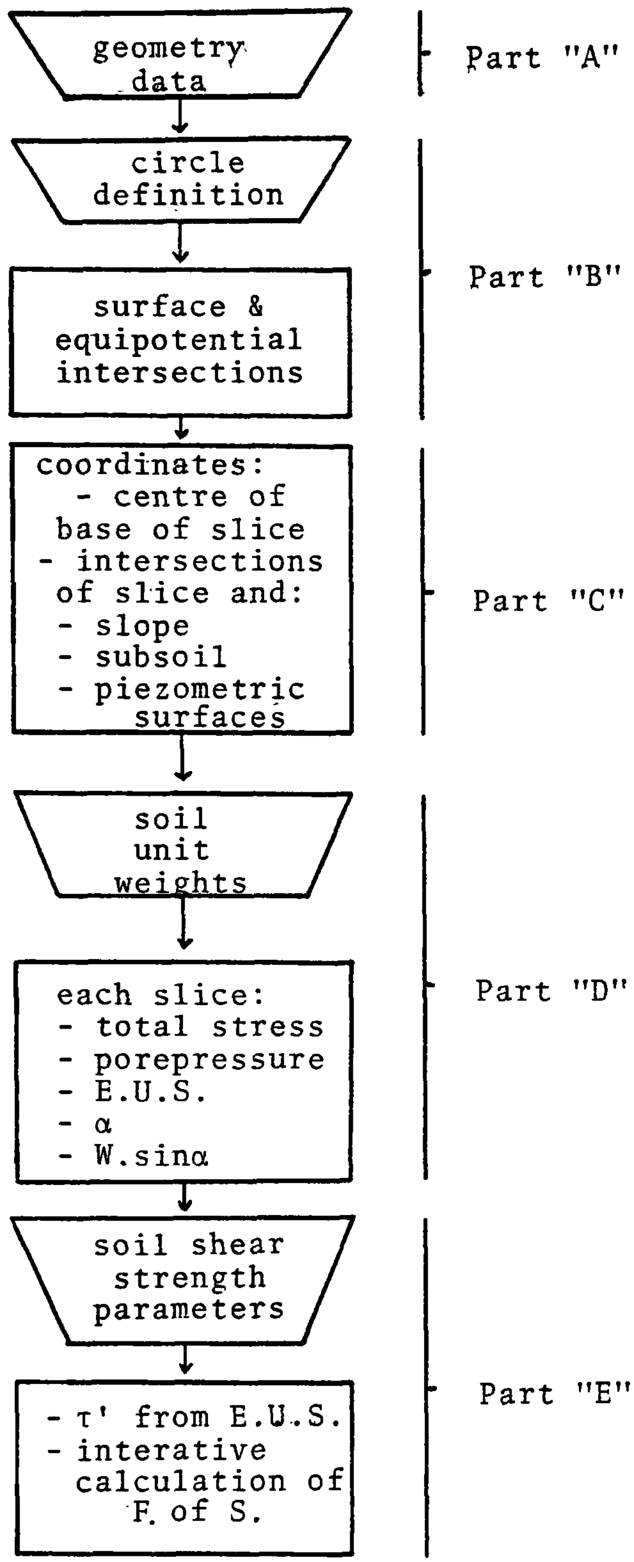


Figure 6.5 GENERAL FLOWCHART FOR THE TI-59 VERSION

The second subprogram reads in the failure circle data, and calculates the two intersections of the failure circle and the slope surface, the width of the slices and the intersections of the defined failure arc and the equipotential lines. The printing of the codes "1" and "2" at the end of the run calls for the third magnetic card to be read in.

The third subprogram computes the coordinates of the center of the base of the slice, and the intersections of the center of the slice with the slope surface, the subsoil interface and the piezometric surface. The next subprogram is called in by the previously mentioned codes. A subroutine of this subprogram on a separate magnetic card is called in, as required, to calculate equipotential ratios.

The fourth subroutine calls in the moist and saturated unit weights of the two soil types (codes WW and WS 1 and 2), and computes the effective unit stress acting at the base of each slice, the total shear stress for the entire mass above the failure surface, and the α angle and length of the base for each slice. The program then asks for the soil shear strength parameters and for the input of the last magnetic card.

The fifth subroutine determines the effective shear strength at the base of each slice and sums the appropriate values to determine the factor of safety by the iteration of the Bishop equation.

For subsequent analysis using the same basic slope geometry, the user need only read in the magnetic card recorded in step 1, and restart the analysis from step 2 by reading in the second part of the program.

6.9.3 Method of Use

The use of this program calls for a certain degree of interaction between the user and the calculator, since the flow of the program is controlled by the user and that the machine asks for the data as required. Because of this feature few controls are used in the program; the user may interrupt the execution of the program at any stage without disturbing the flow of the computations and may similarly obtain listings of the data in memory. The punching of a subroutine code name will redirect the program flow. It is highly recommended that the user have a working knowledge of the TI-59 before attempting to use the present program.

The program requires a geometry layout and data preparation similar to that previously described in this chapter. The use of the program is very straight forward since the program will print out an indication of the type of information required. The procedure for using the program is clearly described in Figure 6.6. Example runs are given in Appendix F.

6.9.4 Output

The only output printed directly by the program is the factor of safety. Supplementary output may be obtained by listing the data contained in the memory banks at the end of the different steps in the execution of the program: the significance of each variable stored in each register is indicated in the "register accounting" given at the end of each subprogram in the program listing in Appendix E.

The two program versions presented in this study offer the basic tool required for most slope stability analyses in Champlain Sea clays. Both of these versions can handle equal pressure nets and non-uniform soil shear strengths; the basic program is sufficiently simple and documented so as to be adaptable to hand-held programmable mini-calculators.

Figure 6.6 - Summary of Procedure for the TI-59 Program

1- Turn calculator on.

2- Press "1", read in side 1 of card A.

3- Press "2", read in side 2 of card A.

4- Press "A" to start the program.

5- Punch in data as asked by the program: X and Y-coordi-tes of
   - the slope surface,
   - the subsoil interface,
   - the piezometric surface, and
   - the equipotential lines.

   note:a) For data end of file before saturation of the data memory, press: (or if no data)
   - "B", during the slope data,
   - "C", during the soil interface data,
   - "D", during the piezometric data, and
   - "E", during an equipotential line data.

   b) If the piezometric surface is the same as the slope surface, press "2nd B'" when the program calls for the piezometric surface coordinates.

   c) Press "2nd E'" if the end of the data set is before memory saturation.

6- At the end of part A, the program demands to read in the data set on magnetic card: this is done by inserting the required card side and punching R/S. The same procedure is applicable to read in part B.

7- For all the other parts of the program (B, C, D, E), the program is initiated by pressing "A"; the program will print out "1" and "2" to indicate to read the next part. The input is clearly asked by the machine, and the factor of safety is given at the end of part E.

8- To restart the program at any subroutine, after the end of part E, press "-1" and "-2" to read in the data set previous to that routine and the routine itself. The program can thus be reinitialized to do the same basic analysis but with different soil shear strength properties, unit weights or failure circles, without requiring a complete repunching of all the data.

CHAPTER 7

RESULTS AND DISCUSSION OF RESULTS

7.1 Presentation of Results

The results of the Fortran computer run are indicated on tables 7.1, 7.2 and 7.3. On each table is shown the lowest computed factor of safety for 30-, 50-, and 70-foot high slopes respectively and for the various soil shear properties and groundwater flow conditions assumed in the analysis. The factors of safety are listed for Mohr-Coulomb envelopes with cohesion intercepts of zero and 1 psi (6.6 kPa) The results obtained using the straight line failure envelopes and mean shear strength parameters, as used by Klugman and Chung (1976) in their parametric study, are also indicated. The geometry, groundwater and soil conditions used in the analysis have been previously adequately described in Chapter V. The relative position of the failure surface to the toe of the slope is also indicated in the tables by the arrows for each factor of safety.

For the 50 foot slope, two factor of safety values are indicated for each data set using the cohesionless soil properties. The lowest of these two values corresponds to an extremely shallow failure surface. These shallow failure

TABLE 7.1 SOIL FAILURE ENVELOPE - 30-FOOT SLOPE

FLOW CONDITION	Soil Type	TRUE c'=0	TRUE c'=1 psi	LINEARLY APPROXIMATED	φ'= 33° c̄'= 200 pcf
HYDROSTATIC	BB	s↑0.58	←1.18	←1.07	
	SN	s↑0.44	←0.92	←0.85	←0.96
	C	s↑0.36	←0.75	←0.63	
PARALLEL to SLOPE FLOW	BB	s↑0.58	↓1.63	↓1.45	
	SN	s↑0.45	←1.27	←1.12	←1.22
	C	s↑0.36	←1.06	←0.91	
INFINITE UNIFORM SOIL	BB	s←0.83	↓1.53	↓1.36	
	SN	s←0.64	↓1.22	↓1.07	←1.20
	C	s←0.51	←1.01	←0.82	
UNCONFINED AQUIFER at TOE of SLOPE	BB	s↑0.13	←1.50	←1.37	
	SN	s↑0.10	←1.17	←1.04	←1.19 ↓1.15
	C	s↑0.08	←0.95	←0.81	
CONFINED AQUIFER BELOW SLOPE TOE	BB		←0.41	↓0.69	
	SN		←0.32	←0.40	←0.62
	C		←0.28	←0.12	

LEGEND SITES

BB - Bearbrook

SN - South Nation

C - Castor River

POSITION OF FAILURE SURFACE

↑ above toe

← at toe

↓ below toe

s shallow failure surface

TABLE 7.2 SOIL FAILURE ENVELOPE - 50-FOOT SLOPE

FLOW CONDITION	Soil Type	TRUE c'=0	TRUE c'=1 psi	LINEARLY APPROXIMATED	φ'= 33° c'= 200 pcf
HYDROSTATIC	BB	↓1.26 s↑1.14	↓1.27	↓1.09	
	SN	↓1.00 s↑0.86	↓1.02	↓0.89	↓1.01
	C	↓0.85 s↑0.76	↓0.86	←0.77	
PARALLEL to SLOPE FLOW	BB	↓1.40 s↑1.25	↓1.44	↓1.27	
	SN	↓1.11 s↑0.95	↓1.15	↓1.03	←1.13
	C	↓0.92 s↑0.76	↓0.94	↓0.94	
INFINITE UNIFORM SOIL	BB	↓1.44 s↑1.32	↓1.49	↓1.30	
	SN	↓1.14 s↑1.01	↓1.19	↓1.04	↓1.10
	C	↓0.94 s↑0.81	↓0.96	↓0.93	
UNCONFINED AQUIFER at TOE of SLOPE	BB	←1.47 ↓1.29 s↑1.25	←1.49 ↓1.33	←1.27 ↓1.19	
	SN	←1.14 ↓1.02 s↑0.96	←1.15 ↓1.07	←1.01 ↓0.96	←1.18 ↓1.10
	C	←0.96 ↓0.89 s↑0.76	←1.01 ↓0.92	←0.88 ↓0.87	
CONFINED AQUIFER BELOW SLOPE TOE	BB		↓0.28	0.49	
	SN		↓0.22	0.27	0.41
	C		↓0.20	0.08	

LEGEND SITES

BB - Bearbrook
SN - South Nation
C - Castor River

POSITION OF FAILURE SURFACE

↑ above toe
← at toe
↓ below toe
s shallow failure surface

TABLE 7.3 SOIL FAILURE ENVELOPE - 70-FOOT SLOPE

FLOW CONDITION	Soil Type	TRUE c'=0	TRUE c'=1 psi	LINEARLY APPROXIMATED	$\phi' = 33^{o}$ c' = 200 pcf
HYDROSTATIC	BB	↓1.22	↓1.22	↓1.12	
	SN	↓0.93	↓0.97	↓0.94	↓ 1.03
	C	↓0.73	↓0.74	←0.87	
PARALLEL to SLOPE FLOW	BB	↓1.34	↓1.34	↓1.29	
	SN	↓1.07	↓1.07	↓1.08	←1.16
	C	↓0.78	↓0.79	←1.03	
INFINITE UNIFORM SOIL	BB	↓1.27	↓1.30	↓1.22	
	SN	↓1.00	↓1.05	↓0.99	↓1.07
	C	↓0.77	↓0.80	↓0.83	
UNCONFINED AQUIFER at TOE of SLOPE	BB	↓1.32	←1.53 ↓1.33	←1.22	
	SN	↓1.06	←1.21 ↓1.07	↓1.09	←1.20 ↓1.15
	C	↓0.78	←0.96 ↓0.79	←1.01	
CONFINED AQUIFER BELOW SLOPE TOE	BB		↓0.21	↓0.39	
	SN		↓0.18	↓0.23	↓0.31
	C		↓0.16	↓0.07	

LEGEND

BB - Bear Brook
SN - South Nation
C - Castor

POSITION OF FAILURE SURFACE

↑ above toe
← at toe
↓ below toe

surfaces, indicated by the symbol s, are also shown in the table of the 30-foot slope.

Two factor of safety values are also shown for the unconfined aquifer draining the toe of the slope condition, when the lowest factor of safety is given by a failure surface located below the toe of the slope. These lower values may be used to evaluate the stability of a slope where a drained permeable horizon, located below the base of a slope, defines an unconfined aquifer condition (no artesian pressures). The higher values are more representative of the case where the stiff aquifer at the base of the slope only allows for failure surfaces at or above the toe of the slope.

The following is a brief discussion and comparative analysis of each set of results.

7.2 General Discussion of Results

The right-most column in the tables contains the factors of safety obtained using the average soil parameters suggested by Klugman and Chung (1976) in their parametric study. These values are very close to unity for the hydrostatic case which was assumed to be the worse possible conditions in their analysis. Higher factors of safety were obtained for conditions representing a flow parallel to the slope, an infinite clay layer and a permeable horizon at the toe of the slope; these higher values indicate, as expected, a greater stabilizing effect of the downward flow component. Much lower values, well below unity, were generated by the confined aquifer condition which is represented by a permeable layer below the base of the slope. Such a case entails a large upward flow component which, at limiting conditions, tends to reduce the effective normal stress to zero, this results is an analysis with conditions close to a frictionless analysis.

The individual shear strength envelopes, representative of the soil properties observed at the three locations used as examples, give a range of factors of safety indicative of the differences in soil shear strength which may be expected in the Ottawa area. This difference in factors of safety caused by the variations in soil properties is noticeably greater for cases where the soil is assumed to experience higher effective normal stresses.

Since this study is not concerned with the correlation of slope gradients and slope heights, the chosen combination of these factors is designed to generate approximately the same factor of safety for a given set of soil and porewater pressure conditions at different slope geometries.

7.3 Slope Geometry

Table 7.4 shows the calculated mean and standard deviation of the factors of safety for the different sets of conditions using the c' = 1 psi (6.6 kPa) true and linearly approximated failure envelopes as listed in the previous tables.

If a higher slope is more sensitive to variations in the groundwater state or in the soil shear properties than is a lower slope, the scatter of factor of safety values would presumably increase with an increase in slope height for the range of extreme conditions analysed. Basically, the standard deviation established for each slope geometry indicates a similar scatter of the factors of safety for the three different slope heights. This homogeneous scatter of safety coefficients from one slope geometry to another demonstrates that a higher slope does not require a more precise evaluation of the subsurface water flow conditions, or of the soil shear strength behaviour, than does a lower slope. Minor variations of these parameters would not entail a greater change in the stability of a higher slope than it would in a moderately low slope.

TABLE 7.4 CALCULATED MEANS AND STANDARD DEVIATIONS OF FACTORS OF SAFETY

	MEAN	STANDARD DEVIATION
Combined true and approximated envelopes		
30 foot slope	0.96	0.39
50 foot slope	0.93	0.39
70 foot slope	0.90	0.40
Hydrostatic	0.95	0.18
Parallel	1.16	0.22
Infinite	1.12	0.22
Unconfined Aquifer	1.15	0.22
Confined Aquifer	0.28	0.16
Separate true and approximated envelopes		
30 foot slope, true	1.01	0.42
approximated	0.91	0.36
50 foot slope, true	0.98	0.43
approximated	0.88	0.36
70 foot slope, true	0.90	0.43
approximated	0.89	0.37
Combined geometry and groundwater conditions		
True failure envelope (c'=1 psi)		
Bearbrook (BB)	1.19	0.48
South Nation (SN)	0.94	0.38
Castor River (C)	0.77	0.30
Linearly approximated failure envelope		
Bearbrook (BB)	1.11	0.32
South Nation (SN)	0.87	0.31
Castor River (C)	0.71	0.34

On the other hand, the mean factor of safety value decreases with an increase in slope height for all of the analysed conditions. The slope geometries were all designed to yield approximately the same factor of safety under the assumed typical hydrostatic porewater pressure distribution. The lower mean factor of safety for the higher slopes is thus indicative of the greater stabilizing effect on the lower slopes of the extreme limiting conditions assumed by the strong upward and downward flows. The effect of the porewater pressure distribution on the stability of a slope may then be considered non-uniform with variations in slope height.

7.4 Porewater Pressure Influence

Figures 7.1, 7.2 and 7.3 show plots of the factors of safety for the true failure envelope with a 1 psi (6.6 kPa) cohesion intercept against the different groundwater flow types. The position of the flow types along the ordinate has been adjusted in order to obtain a straight line distribution for the 30-foot slope.

Similar factor of safety values were obtained for the same soil properties with the different slope geometries influenced by the hydrostatic and the drained aquifer at toe conditions. The factors of safety for the remaining three

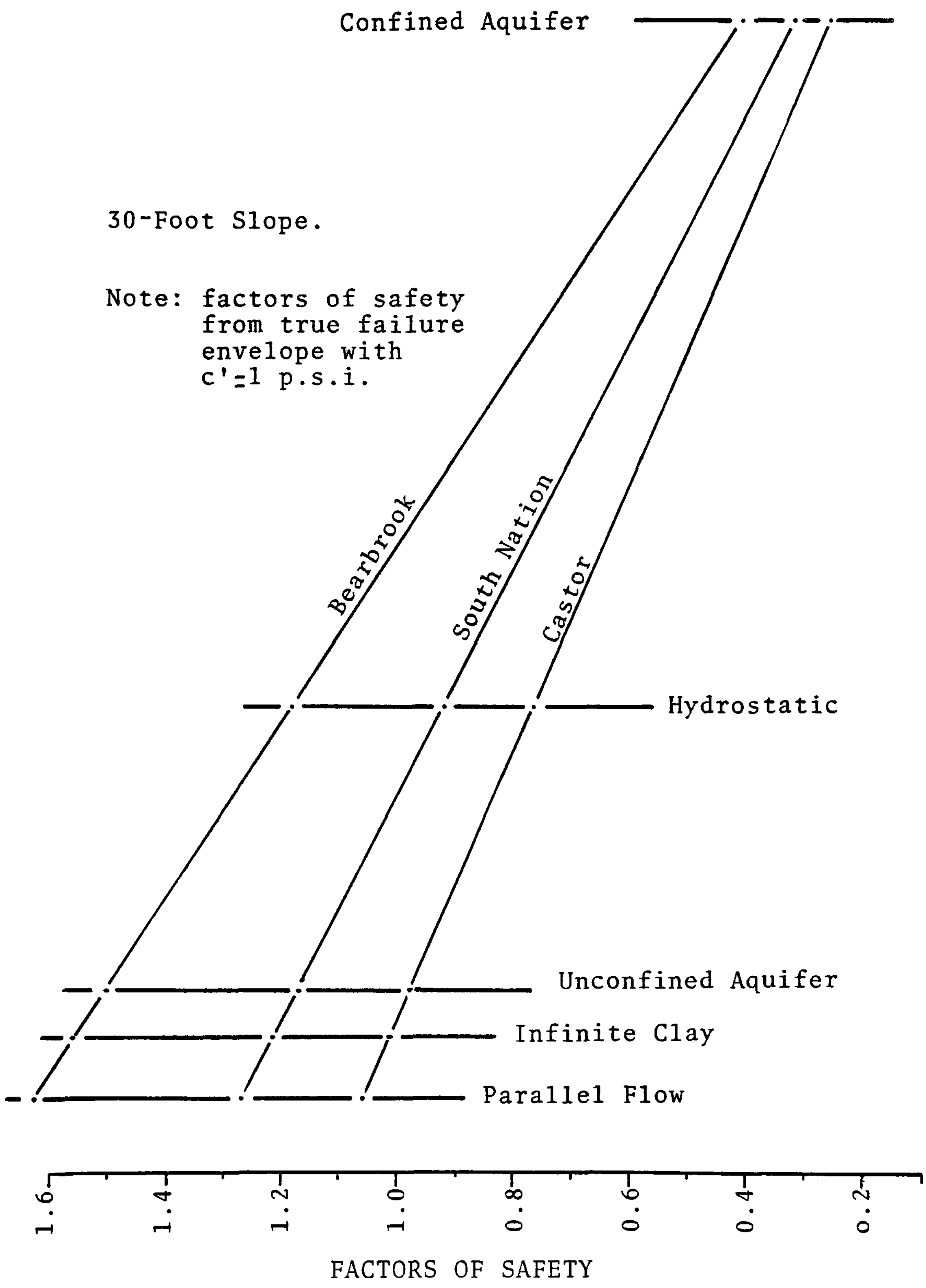


Figure 7.1 FACTOR OF SAFETY vs GROUNDWATER CONDITIONS

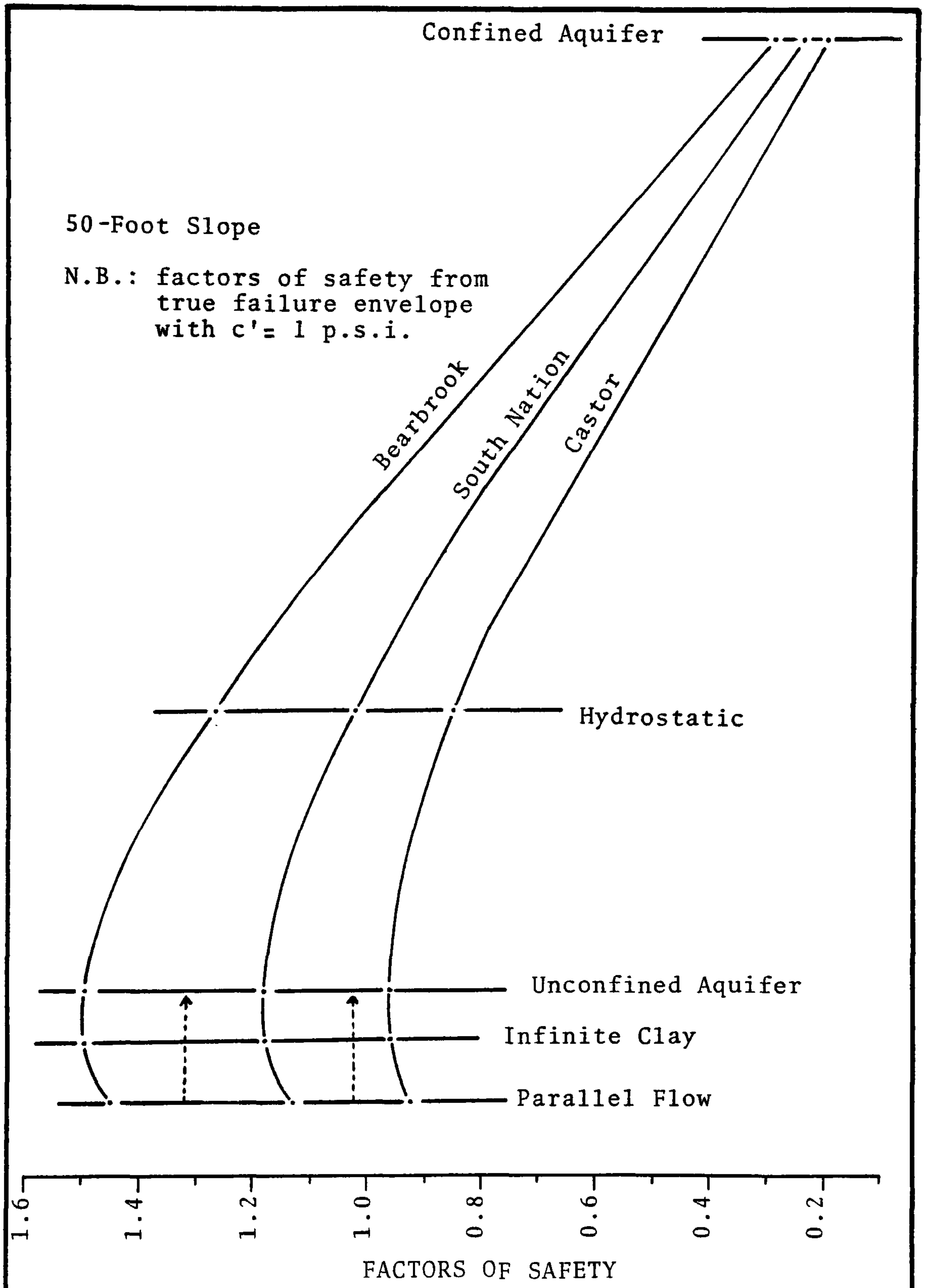


Figure 7.2 FACTOR OF SAFETY vs GROUNDWATER CONDITIONS

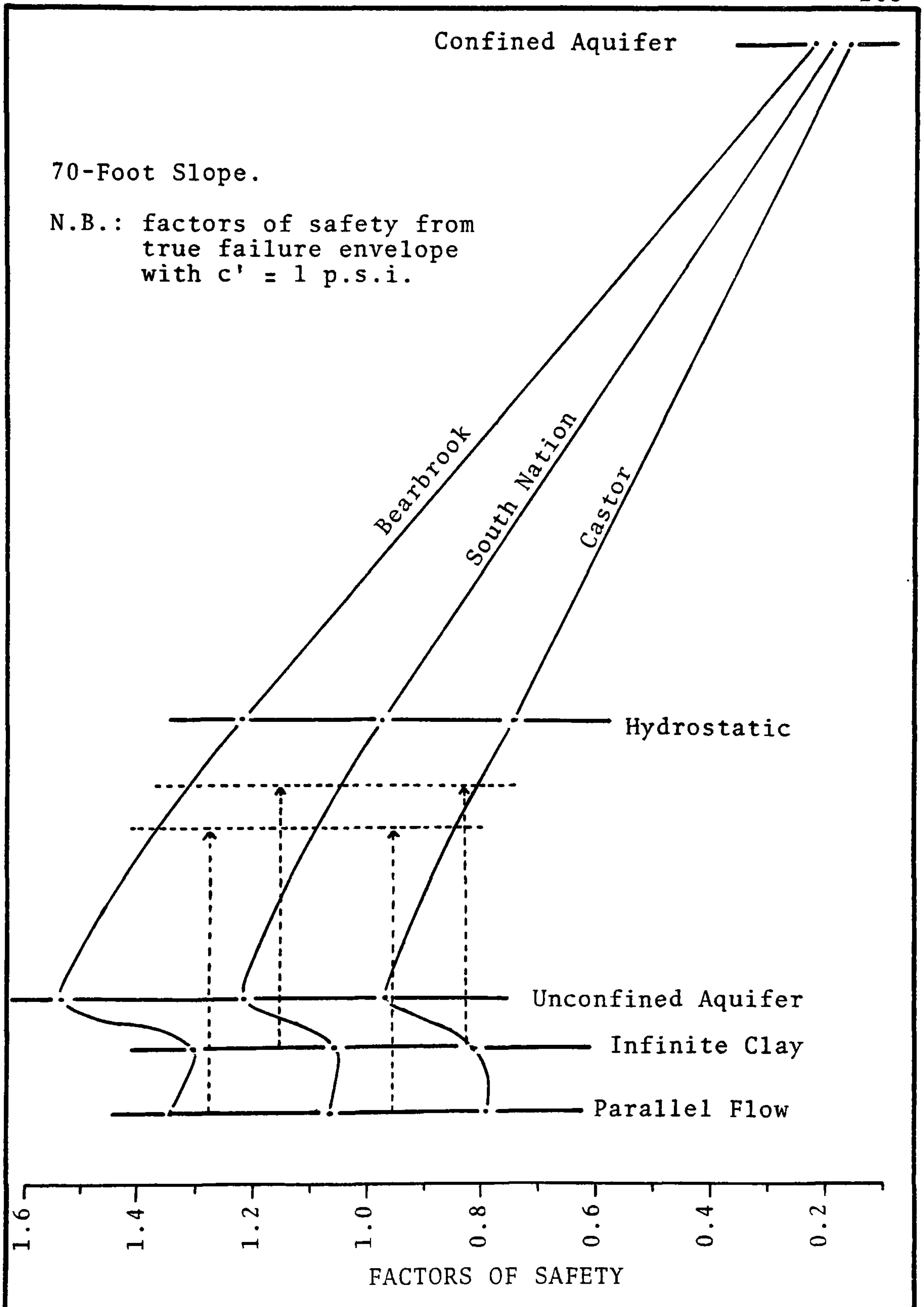


Figure 7.3 FACTOR OF SAFETY vs GROUNDWATER CONDITIONS

flow types generally decrease with an increase in slope height.

In order of increasing stability for the 30-foot slope, the groundwater conditions are classified as follows:

1- confined aquifer,

2- hydrostatic,

3- aquifer at toe,

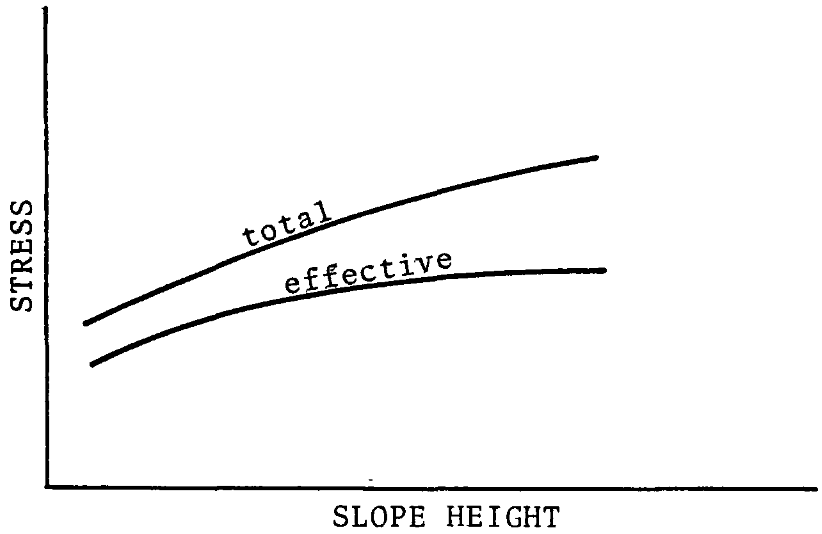
4- uniform soil to infinite depth, and

5- parallel to slope flow.

When the factor of safety data for the 50- and 70-foot slopes is plotted to the same graphical scale as the 30-foot slope data, the above mentioned stability order of porewater pressure distributions is partially inverted for the most stable conditions. For the 50-foot slope, the parallel to slope flow has a slightly lower safety factor than both the infinite and the aquifer at toe cases. For the 70-foot slope, both the parallel flow and the uniform soil cases show lower values than the aquifer at toe condition; these values are close to the factor of safety resulting from the hydrostatic porewater pressure distribution. The uniform soil case entails a weaker state than the parallel flow for high slopes.

An attempt to explain the inversion of the stability effect of the downward flows with increasing slope height may be given by the non-proportional increase of the available shear strength along a potential failure surface which accompanies an increase in the overturning moment of the sliding body. The available shear strength is conditioned by the porewater pressure distribution along the rupture surface; the overturning moment is related to the slope height which controls the position of the failure surface and the mass of the sliding body (total stress).

In a uniform clay slope, there is a downward flow at the crest of the slope; near its base there is a groundwater flow direction transition zone where the conditions vary from hydrostatic to an upward flow at the toe. This transition zone carries high porewater pressures and any increase in the slope height will raise the position of this potentially weak area. This results in a different rate of increase for the effective stress than for the total stress when the potential sliding surface, on which these stresses act, is extended through an increase in the height of the slope. The relationship between the two different rates of increase for the effective and total stresses, as well as the resulting stabilizing and overturning moments relationship, are illustrated in Figures 7.4 a and b. Thus, for the groundwater flow cona)



b)

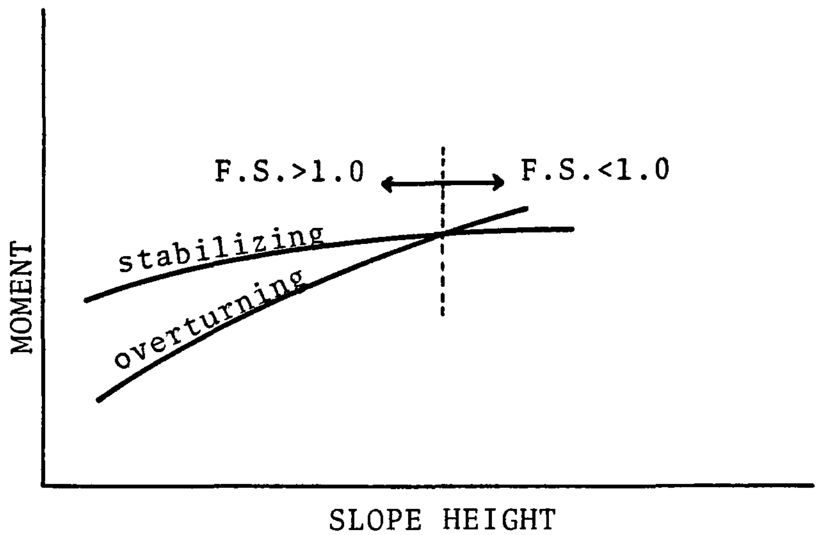


Figure 7.4 SCHEMATIC REPRESENTATION OF THE DIFFERENT RATES OF INCREASE FOR
a) EFFECTIVE vs TOTAL STRESSES AND
b) STABILIZING vs OVERTURNING MOMENTS

WITH A SLOPE HEIGHT INCREASE FOR A UNIFORM SOIL SLOPE.

ditions typical of a uniform clay slope, any increase in the total shear strength due to a slope height increase will be accompanied by a much greater increase in the total weight of the sliding mass. For the parallel to slope flow, the overall decrease in available shear strength with an increase in total stress is similar to the previously described condition, except that the more uniform porewater pressure distribution will yield a more gradual effect which is less critical at higher slopes.

The behaviour of a slope with a drained aquifer at the toe is similar to that of the parallel to slope surface flow condition except that below toe circles cannot be generated due to the presence of the aquifer horizon which is assumed to have a higher shear strength than the overlying clayey material in the present analysis. If the permeable horizon shows weaker shear properties similar to those of the overlying clay, or if the unconfined aquifer is located below the base of the slope, failure surfaces can extend below the toe of the slope. The factor of safety for such failure arcs would be close to or slightly lower than the values obtained for the parallel to slope surface flow case due to the higher hydrostatic porewater pressure assumed to exist in a saturated unconfined aquifer.

7.5 Effect of Soil Shear Properties

7.5.1 Cohesion

The present analysis allows a comparison between the use of c'=0 and a low cohesion value of c'= 1 psi (6.6 kPa) for the same shear strength envelope. The results obtained from these two sets of values were shown on tables 7.1 through 7.3 inclusively.

All the 30-foot high slopes analysed with the zero τ'-intercept generated shallow failure circles with very low factors of safety. The trend in the factor of safety grid distribution is fairly uniform and the only observed distribution locus is at the intersection limit between failure arcs and the slope surface. An example of this type of distribution is shown in Figure 7.5. The factor of safety distribution for the 50-foot slope shows two loci, the lowest of which is at the intersection limit, and the other, of slightly higher value is farther in the slope (Figure 7.6). Shallow failure circles were not examined for the 70-foot slope. Because a c'=0 condition generates a zero shear strength at $\sigma_n'=0$, factors of safety for the confined aquifer case were not calculated since these tended toward a zero value.

1.49	1.40	1.35	1.34	1.02	OUT
1.45	1.37	1.30	1.09	0.62	OUT
1.40	1.33	1.27	0.95	OUT	OUT
1.36	1.29	1.23	0.93	OUT	OUT
1.31	1.26	1.21	0.89	OUT	OUT
1.27	1.19	0.99	0.78	OUT	OUT
1.25	1.16	0.87	0.36	OUT	OUT
1.22	1.21	0.92	OUT	OUT	OUT
1.22	1.28	1.02	OUT	OUT	OUT

F = 1.00

F = 0.50

Figure 7.5 FACTOR OF SAFETY GRID DISTRIBUTION

30 FOOT SLOPE $c' = 0$

(locus located at the intersection limit)

1.46	1.37	1.30	1.23	1.05	OUT
1.42	1.34	1.26	1.17	1.04	OUT
1.38	1.30	1.22	1.12	OUT	OUT
1.33	1.26	1.17	1.08	OUT	OUT
1.30	1.24	1.12	1.07	OUT	OUT
1.26	1.17	1.12	1.06	OUT	OUT
1.24	1.13	1.17	0.76	OUT	OUT
1.21	1.15	1.19	OUT	OUT	OUT
1.20	1.20	1.14	OUT	OUT	OUT

Figure 7.6 FACTOR OF SAFETY GRID DISTRIBUTION

50 FOOT SLOPE $c' = 0$

(two loci: one in-slope and the other at the intersection limit).

Generally, for both the 30- and 50- foot slope, the factors of safety obtained using a cohesion intercept of 1 psi (6.6 kPa) are considerably higher and more coherent than those obtained with the c'=0 analysis. The c'=1 psi (6.6 kPa) analysis results are in approximately the same range of values as those obtained from the use of the linearly appro- ximated envelopes and of the fixed shear parameters assumed by Klugman and Chung in their study. Though these failure surfaces may still be qualified as shallow, they are located will within the slope and are surrounded by failure arcs having higher factors of safety.

The 50-foot slope allows an excellent comparison of the results obtained using the different assumed cohe- sions, since the double loci distributions obtained with the c'=0 condition yields different values for both the shallow and the in-slope minimum factors of safety. The in- slope factors of safety are generally lower than the 1 psi (6.6 kPa) cohesion analysis by a value less than 0.05, with a mean difference of about 0.02 to 0.03. Such differences can be considered as negligible in a slope stability investiga- tion, in view of the approximations usually required and the precision of the factor of safety which is generally expressed to one decimal only, and may be attributed to the lower shear strength generated by the c'= 0 analysis in the very low effective normal stress range.

This study indicates that very low cohesion values may be used to remove the extremely shallow fictitious failure circles generated by a c'=0 parameter in a slope stability analysis without seriously affecting the factor of safety. The use of a low cohesion intercept may also reproduce the stabilizing effect of an upper shallow weathered profile, as previously discussed in chapter V.

7.5.2 True and Approximated Failure Envelopes

The lowest factors of safety obtained using the true soil failure envelope with a 1 psi (6.6 kPa) cohesion and the linearly approximated failure envelope were indicated in tables 7.1 to 7.3 inclusively. The computed mean and standard deviation for these values were shown in table 7.4.

Generally the linearly approximated shear strength envelope has lower factors of safety than the true curved Mohr-Coulomb envelope. This difference in factors of safety is greater for the higher strength soils under conditions of low porewater pressure and are presumably caused by variations in shear strength entailed by the different positions of the two envelopes at a given effective normal stress. For the present soil types, these differences in position reach a maximum at the high-low and lower-intermediate stress range, and are more pronounced for highly curved envelopes such as those presented by the greater shear resistant Champlain Sea clay (Bearbrook).

The higher porewater pressure conditions generate lower effective normal stresses, reducing the difference between the two curves. Under extremely low effective stresses, the influence on the frictional component is greatly reduced, the shear strength being mostly generated by the cohesion component of the soil's resistance. This is illustrated in Tables 7.1 to 7.3 by the factor of safety values obtained for the confined aquifer case. For this condition, the linearly approximated envelopes of the two more resistant soils show higher factors of safety than the true envelope because their cohesion intercept is greater; for the weaker soil, the cohesion of the approximated envelope is weaker than the cohesion assumed for the true envelope; and the factors are proportional to the assumed τ'-intercept value.

Standard deviations of the values obtained from the true failure envelopes are generally slightly higher than those of the approximated envelopes due to a less uniform shear strength distribution generated by a curved strength-normal stress relationship.

The difference in factors of safety between the approximated and true failure envelopes has a maximum value of approximately 0.21 for the examined conditions, with an average difference of about 0.16. This amount of variation in the factor of safety may be considered as acceptable for standard geotechnical slope investigations where high factors of safety, in the order of 1.5 or greater are sought. A linear approximation of the Mohr-Coulomb envelope may be less applicable to strongly curved failure envelopes in the intermediate porewater pressure range since an appreciable difference in shear strength may be introduced by the approximation. For a more critical evaluation, or for strongly curved failure envelopes, it is recommended that the true curved envelope be used instead of a straight line fitted to the Mohr-Coulomb envelope.

The amount of variation in factor of safety values between the different soil types within the same porewater and geometry conditions reaches 0.6 and averages at about 0.40 for both the true and approximated envelopes. This high value indicates that variations in soil shear strength properties are too great to use as a single set of shear parameters and groundwater conditions to represent slope behaviour in the Ottawa area. Past studies (Toombs, 1974) have suggested that the shear behaviour of a clayey soil may be adequately evaluated from in situ vane tests for the precision normally required in most routine geotechnical investigations.

7.6 Comments

The present study indicated that, though slopes of different heights showed approximately similar behaviours at hydrostatic conditions, the effect of varying the groundwater flow type for different combinations of slope height and gradient is not uniform.

Higher slopes have a more uniform behaviour under hydrostatic and downward flow conditions than the lower slopes which show a greater variation in the factors of safety between these different types of porewater pressure distributions. If hydrostatic conditions or a downward flow gradient are assumed for high slopes, the precise evaluation of the flow regime is less critical since these flow types have a more uniform effect than in low slopes where they are related to much stronger variations in factors of safety.

The stabilizing effect of a downward groundwater flow regime is not only less pronounced in higher slopes, but may in fact be reversed in very high slopes. A change in groundwater flow condition which increases the stability of a low slope may decrease the computed factor of safety for a much higher slope. This is an important consideration in the stabilization of high slopes where an increase in the downward component of the groundwater flow direction may not necessarily increase the overall stability, depending on the previously existing flow regime.

The above considerations results in a lower average factor of safety for higher slopes, indicating that high factors of safety may best be obtained by the use of an adequate slope gradient in high slopes. Since variations in the flow regime have more effect on low slopes, modifications to the porewater pressure distribution may be sufficient to attain the degree of stability required on low slopes.

Though the present study gives indications on initial slope failures, it does not take into consideration the cumulative effect of slope height on the stability, as translated by the susceptibility of high slopes to retrogressive sliding. The part of the study dealing with various soil properties suggests that retrogressive sliding may be related to the removal of part of the superficial fissured horizon and the soil's cohesionless behaviour under this capping. On a low slope, an initial slope rupture will cause the accumulation of a certain quantity of debris at the base of the slope which will have a stabilizing effect due to the redistribution of effective stresses onto the most unstable part of the slope. On higher slopes, the stabilizing effect of the debris is more localized and the removal of material at the higher levels may allow the effective normal stresses to be reduced to a negligible value at the levels where very high porewater pressures may be acting depending on the flow regime. The extent of a retrogressive slide is then controlled by the modification of the slope geometry caused by the successive accumulation of debris, and by the changes in the groundwater flow regime in response to the new geometry and surface stratigraphy.

The confined aquifer conditions presented in this study is at the extreme limit of feasibility since negative effective normal stresses are generated in the soil mass (porewater pressure greater than the soil weight). Such stresses are impossible and are readjusted to zero by the program. A finely adjusted flow net would, at the limit of the highest possible porewater pressures, generate zero effective normal stresses which would result in a frictionless analysis (deepest possible failure circles). Since deep failure surfaces are seldom observed in slope ruptures in the Ottawa area, it may be assumed that extreme upward flow conditions are not common, and that at worst an intermediate condition between the confined aquifer and hydrostatic case may exist in a slope.

CHAPTER 8

CONCLUSIONS

8.1 General

This chapter presents a brief review of the study and its major conclusions. Suggestions for further investigations are also discussed.

8.2 Summary of Study

The stability of three slopes of fixed height and surface geometry has been investigated for various soil shear properties and groundwater flow conditions. The heights were chosen to correspond to typical slopes of the Ottawa area; the slope gradients were determined from the literature for a factor of safety of approximately one. Actual soil properties, as well as shear strength parameters assumed in past studies, have been examined. Five possible groundwater conditions which could exist in a slope have been discussed and used in the analysis.

Since the parameters used in this study cannot be directly handled by any known computerized analysis method, a computer program has been written for the analysis. This program is based on the Bishop modified expression and can handle both actual flow nets and curved Mohr-Coulomb envelopes. A comprehensive documentation has been prepared for the program. In view of the facilities normally available to a user, two versions are offered. The main version is written for the University of Ottawa IBM 360/365 and offers extensive user facilities. A more limited version, written for a Texas Instrument TI-59 programmable mini-calculator, is also presented.

The results and main points concluded from this study have been discussed in Chapter 7 and are hereafter summarized.

8.3 Major Conclusions

The following is a summary of the major conclusions resulting from the present study.

1. No single set of shear strength parameters may adequately describe the Ottawa area Champlain Sea clays for a slope stability investigation.

2. For general slope investigations with a soil showing a weakly curved failure envelope, a linearly approximated envelope established from either laboratory or field testing may adequately describe the soil's strength behaviour.

3. For precise slope stability analyses with a soil having a strongly curved Mohr-Coulomb envelope, the use of the curved envelope, or of a linearly approximated envelope established in consideration of the type of porewater pressure distribution inferred, is required to obtain realistic results.

4. With the conditions normally assumed in a slope stability analysis, a cohesionless soil generates failure surfaces incompatible with those observed in the field. The use of a low cohesion intercept value, approximately equal to the shear strength generated by an effective normal stress of a few feet of submerged soil, allows for a more correct analysis.

5. The computer program used for the present parametric study was designed to handle the conditions measured by field observations. Its hability to handle equipotential nets and curved Mohr-Coulomb envelopes, to des-

cribe the groundwater flow conditions and the soil's shear behaviour, is a valuable tool in determining the stability of slopes where the stability parameters are too complex to be properly considered by the classical assumptions used in geotechnical engineering. The program is sufficiently general to be used whenever the Bishop method of analysis is applicable, and its documentation is sufficient to allow its use by untrained personnel. The Fortran version may be used to handle large quantities of data, such as in the present parametric study, while the mini-calculator version offers more limited capacities in a portable package.

6. The use of hydrostatic conditions to describe the worst porewater pressure distribution in a slope may not be representative of the typical state that may exist at most sites in the Ottawa area.

7. The porewater pressure distribution generating the worst possible conditions for slope stability corresponds to a confined aquifer below the base of the slope. The extreme of this case entails zero effective normal stresses and results in a near frictionless analysis.

8. The groundwater conditions resulting in the highest slope stability is determined by a rigid unconfined

aquifer at slope toe level. If the aquifer has shear properties similar to that of the overlying material, as when toe drains are used to reproduce this condition, the factor of safety is reduced because the hydrostatic porewater distribution in the aquifer reduces the shear strength below the toe of the slope.

9. Lower slopes are more strongly influenced by the stabilizing effect of the downward flow component than higher slopes.

10. In higher slopes, a strong downward flow component near the crest of the slope has the adverse effect of reducing the overall stability.

8.4 Recommendations

Further investigative work should be done to determine the exact effect of the upper weathered material which covers most clay sites in the Ottawa area. This type of study could be combined with an analysis of the precise behaviour of the groundwater flow in the surface zone of slopes in the Champlain Sea clay. This would permit to determine the exact effect of this zone on the stability of slopes and verify the applicability of the suggestion in using a small cohesive intercept to describe the soil's behaviour at shallow depths.

In view of the importance of the groundwater flow regime in slope stability, further study would also be required to determine the exact types of groundwater flow that may be observed in the Ottawa area. Such a study would possibly determine if stratigraphic observations are correlatable with subsurface flow types, and would allow to indicate the most probable worst porewater pressure distribution at a site.

LIST OF APPENDICES

Appendix A

ANALYTICAL GEOMETRY

<u>To resolve the intersection of a circle and a line</u>, (<u>subroutine INTER</u>).

The solution is the roots obtained by resolving the linear in the equation of the circle.

The equation of a line is:

$$Y = S*Y + b \quad \text{\_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_} \quad 1$$

where X and Y are respectively the abscissa and ordinate parts of the coordinate of the root of the equation,

b is the Y-intercept, and

S is the slope of the line

$$S = \frac{Y2 - Y1}{X2 - X1} \quad \ldots\ldots\ldots\ldots \quad 2$$

where (X1,Y1) and (X2,Y2) are the coordinate of two points on the line.

The linear equation may also be written:

$$Y - Y1 = S(X - X1) \ ,$$

$$\text{or } Y = S(X - X1) + Y1 \quad \ldots\ldots\ldots\ldots \quad 3$$

Simultaneously resolving 1 and 3 we have

$$S*X + b = S*X - S*X1 + Y1 \ ,$$

$$\text{or } b = Y1 - S*X1 \quad \ldots\ldots\ldots\ldots \quad 4$$

Resolving 4 in 1,

$$Y = S*X + Y1 - S*X1 \quad \ldots\ldots\ldots\ldots \quad 5$$

The equation of a circle is:

$$R^2 = (X - H)^2 + (Y - G)^2, \quad \ldots\ldots\ldots \quad 6$$

where R is the radius and

(H,G) the coordinates of the center of the circle.

Resolving 5 into 6

$$R^2 = (X - H)^2 + (S*X + Y1 - S*X1 - G)^2 \quad . . 7$$

Since X is the only unknown, we thus have a second degree equation with one unknown which can be resolved in the quadratic equation form of

$$A*X^2 + B*X + C = 0.$$

Expanding equation 7, we get:

$$(X^2 - 2*H*X + H^2) + (S^2*X^2 + 2*S*Y1*X - ...$$
$$...- 2*S^2*X1*X - 2*S*G*X + Y1^2 - 2*S*X1*Y1 - ..$$
$$...- 2*G*Y1 + S^2*X1^2 + 2*S*G*X1 + G^2) - R^2 = 0.$$

Rearranging in the normal quadratic form:

$$X^2 + S^2*X^2 -...$$
$$...- 2*H*X + 2*S*Y1*X - 2*S^2*X1*X - 2*S*G*X +...$$
$$...+ H^2 + Y1^2 - 2*S*X1*Y1 - 2*G*Y1 + S^2*X1^2 +...$$
$$...+ 2*S*G*X1 + G^2 - R^2 = 0 ,$$

and

$$X^2(S^2 + 1) + X(2*S(Y1 - S*X1 - G) - 2*H) +..$$
$$...+ S*X1(S*X1 - 2*Y1 + 2*G) + G(G - 2*Y1) +...$$
$$...+ H^2 + Y1^2 - R^2 = 0.$$

We now have from the normal quadratic form that:

$$A = S^2 + 1 ,$$

$$B = 2*S(Y1 - S*X1 - G) - 2*H , \text{ and}$$

$$C = S*X1(S*X1 - 2*Y1 + 2*G) + G(G + 2*Y1) + \ldots + H^2 + Y1^2 - R^2 .$$

The roots of such a system are given by:

$$\frac{-B \pm \sqrt{D}}{2*A},$$

where D is the discriminant

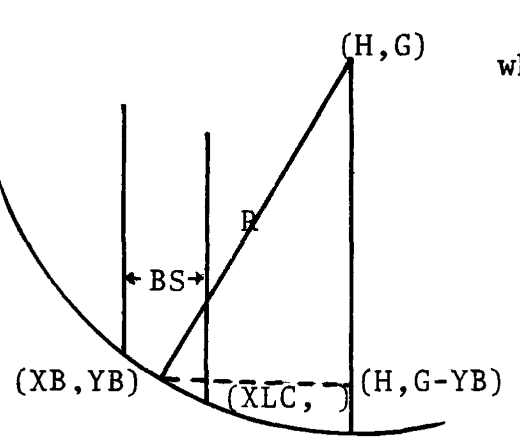
$$D = B^2 - 4*A*C .$$

If D is negative, the roots are imaginary and the line does not intersect the circle.

If D is equal to zero, the roots are real and coincident: the line is tangent to the circle.

If D is positive, the roots are real and different and the line cuts the circle at two distinct points.

<u>To determine the coordinates of the center of the base of a slice</u> (<u>Subroutine FOFS</u>).



where (H,G) represents the coordinates of the center of the circle,
BS, the width of the slice,
R, the circle radius, and
XLC is the abscissa coordinate of the edge of the slice.

The abscissa coordinate of the centre of the base of the slice is:

$$XB = XLC - 0.5*BS.$$

The ordinate coordinate of the center of the base of the slice (YB) can be resolved through the rectangle triangle formed by the points (XB, YB), (H,G) and (H,G-YB). Since the hypothenuse squared is equal to the sum of the squared of the two shorter sides, we have:

$$R^2 = (H - XB)^2 - (G - YB)^2,$$

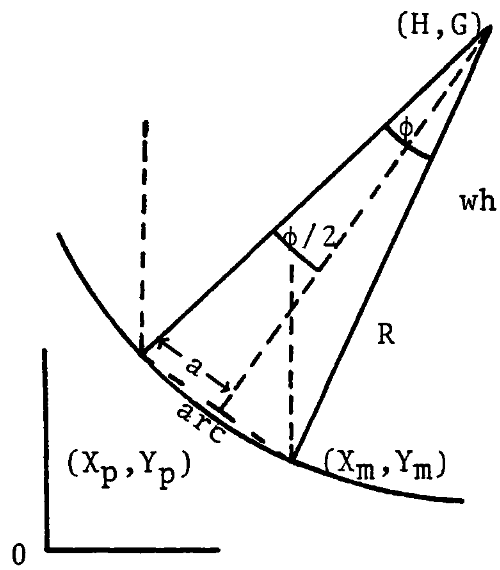
$$(G - YB)^2 = R^2 - (H - XB)^2 ,$$

$$G - YB = \sqrt{R^2 - (H - XB)^2}$$

and

$$YB = G - \sqrt{R^2 - (H - XB)^2} .$$

<u>To determine the arc length of the base of a slice (subroutine FOFS).</u>



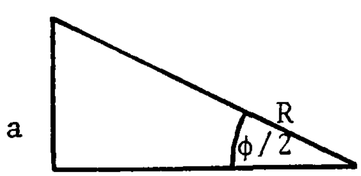
where R is radius of the circle,

ϕ, the angular value of the arc,

a, half the cord,

(H,G), the coordinates of the center of the circle,

(X_p,Y_p) and (X_m,Y_m) are the coordinates of the corners of the base of the slice respectively closest and farthest from the origin,



and $\sin\phi/2 = a/R$ 1

The distance between two points is

$$a = \frac{\sqrt{(X_m-X_p)^2 + (Y_m-Y_p)^2}}{2} \quad . . . . 2$$

Solving 2 into 1, we have

$$\sin \phi/2 = \frac{\sqrt{(X_m - X_p)^2 + (Y_m - Y_p)^2}}{2*R} \quad \text{and}$$

$$\phi = 2*\arcsin\left(\frac{\sqrt{(X_m - X_p)^2 + (Y_m - Y_p)^2}}{2*R}\right) \quad . \; . \; 3$$

We know that:

$$arc = R*\phi \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; 4$$

Solving 3 into 4, we get

$$arc = R*2*\arcsin\left(\frac{\sqrt{(X_m - X_p)^2 + (Y_m - Y_p)^2}}{2*R}\right) \; .$$

<u>To determine the coordinates of the intersection of the center of the slice and any non-paralel line (subroutine FOFS)</u>.

The center of the slice can be assumed to be a vertical line passing through the center of the base of the slice whose coordinates are (XB,YB); the abscissa coordinate of the intersection will thus be XB.

The equation of the non-vertical line may be written

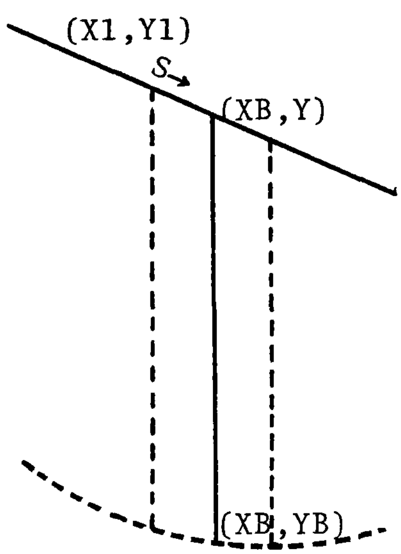
$$Y - Y1 = S*(X - X1)$$

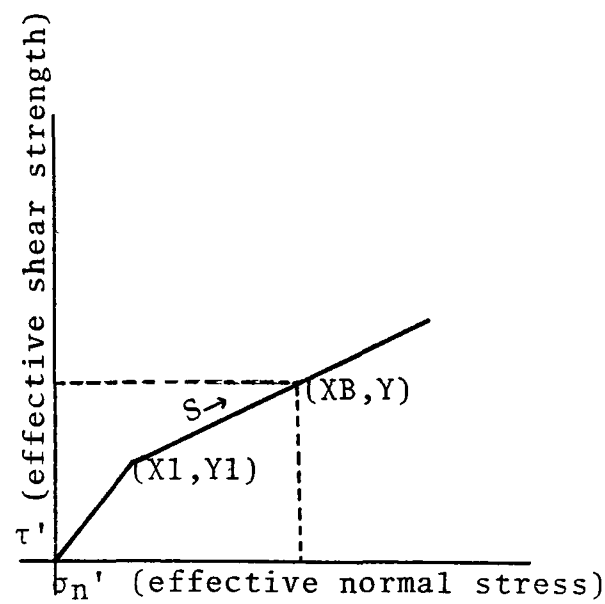
$$\text{or } Y = S(X - X1) + Y1.$$

$$X = XB ,$$

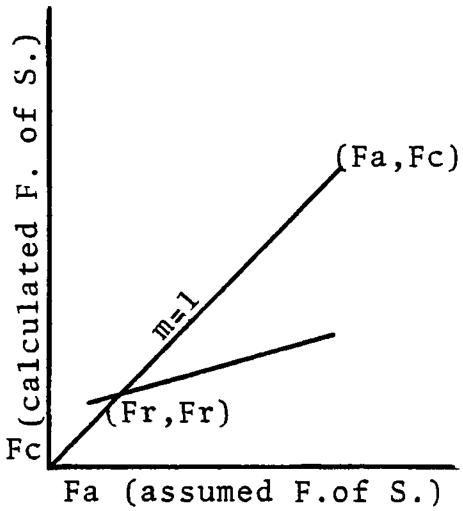
$$Y = S(XB - X1) + Y1 .$$

This solution is also applicable to determine the soil shear strength from the applied stress and the soil Mohr-Coulomb failure envelope.





<u>To determine the true factor of safety value</u> (<u>subroutine FOFS</u>).



The correct solution is a point lying on a 45 degree line passing through the origin since the assumed factor of safety value is equal to the computed factor of safety. To resolve this point is to determine the intersection of two non-parallel lines of which one is a line passing through the origin, point coordinates (0,0), whose slope is equal to one,

$$Fa = Fc = Fr$$

and the other is defined by two points,

$$Fr = Mf*(Fr - Fa) - Fc$$

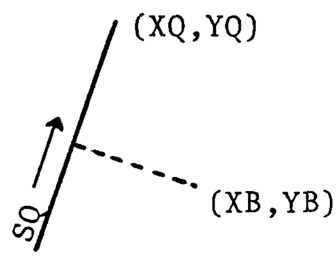
which upon resolving for Fr becomes

$$Fr = \frac{Fc - Mf*Fa}{1 - Mf} ,$$

where Mf is the slope of the line indicating the relationship between assumed and calculated factors of safety.

<u>To determine the normal distance between a point and a line (subroutine WEIGHT).</u>

This solution is used to determine the distance of the center of the base of the slice to the surrounding equipotential lines.



where (XB,YB) are the coordinates of the point, (XQ,YQ), the coordinates of a point on the line and Sq is the slope of the line.

If the equation of a line in the general form is

$$A*X + B*Y + C = 0,$$

the equation for the normal distance between a point and a line is:

$$d = \frac{A*XB + B*YB + C}{\sqrt{A^2 + B^2}} \quad \ldots\ldots\ldots\ldots \quad 1$$

The general equation of the line may be determined from

$$Y - YQ = SQ*\ (X - XQ)$$

or $$SQ*X - Y + YQ - SQ*XQ = 0 \quad \ldots\ldots\ldots \quad 2$$

From equation 2, we have that

$A = SQ$,

$B = -1$ and

$C = YQ - SQ*XQ.$

Solving equation 1 using these values, we obtain

$$d = \frac{SQ*XB - YB + YQ - SQ*XQ}{\sqrt{SQ^2 + 1}}$$

and upon reaaranging

$$d = \frac{YQ - YB + SQ*(XB - XQ)}{\sqrt{SQ^2 + 1}}$$

Appendix B

FORTRAN PROGRAM LISTING

201

```
COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                   SOURCE,EBCDIC,NOLIST,DECK,LOAD,MAP,NOEDIT,ID,NOXREF
          C
          C
          C
          C
          C
          C  *****************************************************************
          C  *****************************************************************
          C
          C
          C      PROGRAM SIOU
          C      SLOPE INVESTIGATION OTTAWA UNIVERSITY
          C      COMPUTES FACTORS OF  SAFLTY FOR SLOPES BY THE BISHOP MODIFIED
          C     METHOD USING A FLOW NET AND A CURVED NORMAL STRESS - SHEAR STRENGTH
          C      RELATIONSHIP.                      G. DESCHAMPS  JULY 1978
          C
          C
          C  *****************************************************************
          C  *****************************************************************
          C
          C
          C
          C
          C
          C  *****************************************************************
          C
          C      COMMON BLOCK TO MAIN PROGRAM AND ALL SUBRCUTINES
          C
ISN 0002         IMPLICIT INTEGER*2(I-N)
ISN 0003         COMMON/BLK/CX(15,15,5),CY(15,15,5),AAC(30,10),GAMAH(30,10),ARCIN(3
                10,10),XB(30,10),YB(30,10),UPORP(30,10),SIG(5,10),
                2TAU(5,10),EQ(32),SQ(32),XQ(32),YQ(32),TANPHI(30,10),TAUE(30,10)
                3,BS(30),ELQ(30),S(30),SEQ(30),X1(30),X2(30),XLC(30),XQ1(30),XQ2(30
                4),Y1(30),Y2(30),YLC(30),YQ1(30),YSS(30)/BKI4/LSL(14)/BLK/CO(10),SP
                5Z(10),WW(10),WS(10),XPZ1(10),XPZ2(10),YPZ1(10),CL(5)
ISN 0004         COMMON/BKI4/LXY(5),NEG(4),L
                6EQ(5),LPZ(4),CIRC,EQPT,LAST,LINE,NEXT,TOT,SOIL,PIEZ/BLK/FS,G
                7,H,R,WD,IS(30),ISJC(30),IST(10)/BKI2/NM(10)/BLK/IN1
                82(5),IN13(5)/BKI2/O,U,T,BLANK,BR,SI/BLK/IEQ,IF,ILAST,IMIN,INEXT,IP
                9Z,IRAD,ISTOP,JF,JRAD,KRAD,NEQ,NF,NN,NPIEZ,NQ,NSOL,NXS,I,J,MM,N1
ISN 0005         INTEGER*2 O,U,T,BLANK,F
ISN 0006         INTEGER*2 NEG
ISN 0007         INTEGER*4 NEXT,LAST,LINE,TOT,PIEZ,EQPT,SOIL,CIRC,LXY,LPZ,LEQ,LSL
ISN 0008         INTEGER*4 BR,SI,DESC,TITL(20)
ISN 0009         INTEGER*4 IFI
          C
          C      DIMENSION BLOCK FOR MAIN
          C
ISN 0010         DIMENSION F(4,15,15,5)
ISN 0011         DIMENSION ACCM(30,10),ARCM(30,10), PORM(30,10),  XBM(
                130,10),YBM(30,10), TAM(30,10),TAUM(30,10)
ISN 0012         DIMENSION BSM(30),IN(4)
          C
          C
          C  *****************************************************************
          C
```

```
                C     WRITE GENERAL TITLE OF PROGRAM
                C
      ISN 0013        WRITE(6,11)
      ISN 0014     11 FORMAT('1',29X,'SLOPE STABILITY ANALYSIS - BISHOP''S MODIFIED METH
                     1OD OF SLICES.',/)
                C
                C
                C ******************************************************************
                C
                C     INITIALIZE TRACERS AND CONTROL VALUES
                C
                C
                C     ISTOP=1, STOP EXECUTION DUE TO INPUT ERROR
      ISN 0015     21 ISTOP=0
                C
                C     IRAD=0, START NEW RADIUS CARD, =1, CONTINUE WITH PRESENT CARD
      ISN 0016        IRAD=0
                C
                C     INEXT=1, INDICATES THAT 'NEXT' CARD HAS BEEN ENCOUNTERED
      ISN 0017        INEXT=0
                C
                C     ILAST=1, INDICATES THAT 'LAST' CARD HAS BEEN ENCOUNTERED
      ISN 0018        ILAST=0
                C
                C     KRAD=1, CIRCLE DOES NOT INTERSECT A GEOMETRY LINE
      ISN 0019        KRAD=0
                C
                C     TO DETERMINE IF PROBLEM ENCOUNTERED AT EXECUTION LEVEL
      ISN 0020        JRAD=0
                C
                C     TO DETERMINE FIRST COMPUTED FMIN
      ISN 0021        FMIN=1000.
                C
                C     NF - COUNTER TO STORE RADIUS CARD DATA
      ISN 0022        NF=0
                C
                C
                C ******************************************************************
                C
                C     READ AND WRITE PROBLEM TITLE
                C
      ISN 0023        READ(5,31)(TITL(I),I=1,20)
      ISN 0024     31 FORMAT(20A4)
      ISN 0025        WRITE(6,41)(TITL(I),I=1,20)
      ISN 0026     41 FORMAT('0',22X,20A4,/)
                C
                C
                C ******************************************************************
                C
                C     READ DATA FIELD DEFENITION CARD
                C
      ISN 0027        READ(5,51)NXS,NPIEZ,NEQ,NSOL,DESC
      ISN 0028     51 FORMAT(4I5,2X,A2)
                C
                C
                C ******************************************************************
                C
                C     CHECK INPUT VALUES ON DATA FIELD DEFENITION CARD
```

```
                C
                C
                C       CHECK IF NXS AND NSOL ARE LOGICAL VALUES
                C
ISN 0029                IF(NXS.GT.0.AND.NXS.LE.30)GO TO 291
ISN 0031                WRITE(6,301)NXS
ISN 0032            301 FORMAT('0',10X,'NUMBER OF CROSS-SECTION CARDS NXS (',I5,' ) IS NOT
                       1 WITHIN SPECIFIED LIMITS.',/)
ISN 0033                ISTOP=1
ISN 0034            291 IF(NSOL.GT.0.AND.NSOL.LE.10)GO TO 311
ISN 0036                WRITE(6,541)NSOL
ISN 0037            541 FORMAT('0',10X,'NUMBER OF SOIL CARDS NSOL (',I5,') IS NOT WITHIN S
                       1PECIFIED LIMITS.',/)
ISN 0038                ISTOP=1
ISN 0039            311 IF(NPIEZ.LT.0.OR.NPIEZ.GT.10) WRITE(6,901) NPIEZ
ISN 0041            901 FORMAT('0',10X,'NUMBER OF PIEZOMETRIC CARDS NPIEZ (',I5,') IS NOT
                       1 WITHIN SPECIFIED LIMITS.',/)
ISN 0042                IF(NEQ.LT.0.OR.NEQ.GT.30) WRITE(6,911) NEQ
ISN 0044            911 FORMAT('0',10X,'NUMBER OF EQUIPOTENTIAL CARDS NEQ (',I5,') IS NOT
                       1WITHIN SPECIFIED LIMITS.',/)
                C
                C
                C       CHECK IF S.I. OR BRITISH SYSTEMS SPECIFIED
                C
ISN 0045                IF(DESC.EQ.SI) WD=1.
ISN 0047                IF(DESC.EQ.BR)WD=62.4
ISN 0049                IF(DESC.EQ.BR.OR.DESC.EQ.SI)GO TO 511
ISN 0051                WRITE(6,501)DESC
ISN 0052            501 FORMAT('0',10X,'INTERNATIONAL OR BRITISH SYSTEM NOT SPECIFIED ON F
                       1IELD DEFENITION CARD, SYSTEM DEFINED READS: ',A2,/)
ISN 0053                ISTOP=1
ISN 0054            511 IF(ISTOP.EQ.1)GO TO 61
                C
                C
                C *****************************************************************
                C
ISN 0056                CALL XSECT
                C
                C *****************************************************************
                C
                C
ISN 0057                IF(ISTOP.EQ.0)GO TO 81
                C
                C
                C *****************************************************************
                C
                C       CHECK FOR PROBLEM TERMINATION,
                C       AND READ DATA TILL PROBLEM TERMINATION.
                C
ISN 0059             61 IF(INEXT.EQ.1.OR.ILAST.EQ.1)GO TO 261
ISN 0061                READ(5,71)DESC
ISN 0062             71 FORMAT(A4)
ISN 0063                IF(DESC.EQ.NEXT)INEXT=1
ISN 0065                IF(DESC.EQ.LAST)ILAST=1
ISN 0067                GO TO 61
                C
                C
                C *****************************************************************
```

```
                C
ISN 0068           81 CALL FCIRC
                C
                C ******************************************************************
                C
                C
                C      CHECK PROBLEM TERMINATION
                C
ISN 0069               IF(ISTOP.EQ.1)GO TO 61
                C
                C
                C ******************************************************************
                C
                C      WRITE FAILURE CIRCLE DATA COLUMN TITLES
                C
ISN 0071               WRITE(6,91)
ISN 0072            91 FORMAT('0',19X,'F OF S    CENTER X   CENTER Y     LEVEL      T.S.S.
                      1  ARC LENGTH',/)
                C
                C
                C ******************************************************************
                C
                C      IPZ=1, FAILURE SURFACE DOES NOT CUT PIEZOMETRIC SURFACE
                C
ISN 0073          1601 IPZ=0
                C
                C      IEQ=1, FAILURE CIRCLE DOES NOT CUT EQUIPOTENTIAL LINES
ISN 0074               IEQ=0
                C
                C
                C ******************************************************************
                C
ISN 0075               CALL INTER
                C
                C ******************************************************************
                C
                C
ISN 0076               IF(KRAD.EQ.1)GO TO 101
ISN 0078               IF(JRAD.EQ.1)GO TO 321
                C
                C
                C ******************************************************************
                C
ISN 0080               N1=NN
ISN 0081           602 CALL FOFS
                C
                C ******************************************************************
                C
                C
ISN 0082               IF(KRAD.EQ.0) GO TO 601
ISN 0084               WRITE(6,1602)H,G,R
ISN 0085          1602 FORMAT(1X,15X,'SHALLOW FAILURE CIRCLE (',F8.1,',',F8.1,' ), OF RAD
                      1IUS: ',F8.1,'.')
ISN 0086               GO TO 101
ISN 0087           601 IF(JRAD.EQ.1) GO TO 321
ISN 0089               IF(FS.LT.0.) GO TO 1001
                C
                C
```

```
                C ********************************************************************
                C
                C     STORE VALUES FOR LOWEST SAFETY FACTOR
                C
ISN 0091          341 IF(FS.GE.FMIN) GO TO 701
ISN 0093              FMIN=FS
ISN 0094              RADM=R
ISN 0095              CXM=H
ISN 0096              CYM=G
ISN 0097              ELM=CL(NF)
ISN 0098              NNM=NN
ISN 0099              DO 531 I=1,NNM
ISN 0100              BSM(I)=BS(I)
ISN 0101              DO 531 J=1,10
ISN 0102              ARCM(I,J)=ARCIN(I,J)
ISN 0103              XBM(I,J)=XB(I,J)
ISN 0104              YBM(I,J)=YB(I,J)
ISN 0105              ACCM(I,J)=GAMAH(I,J)
ISN 0106              PORM(I,J)=UPORP(I,J)
ISN 0107              TAUM(I,J)=TAUE(I,J)
ISN 0108          531 TAM(I,J)=TANPHI(I,J)
                C
                C
                C ********************************************************************
                C
                C     DETERMINE AND STORE ALPHABETIC VALUES OF THE FACTORS OF SAFETY
                C
ISN 0109          701 IFI=FS/100.
ISN 0110              FS=(FS-FLOAT(IFI*100))+0.005
ISN 0111              IN(1)=FS/10.
ISN 0112              IN(2)=FS-IN(1)*10
ISN 0113              IN(3)=FS*10.-IN(1)*100-IN(2)*10
ISN 0114              IN(4)=FS*100.-IN(1)*1000-IN(2)*100-IN(3)*10
ISN 0115              DO 391 I=1,4
ISN 0116              IF(IN(I).EQ.0) IN(I)=10
ISN 0118          391 F(I,IF,JF,NF)=NM(IN(I))
ISN 0119              IF(IN(1).EQ.10)F(1,IF,JF,NF)=BLANK
ISN 0121              GO TO 131
ISN 0122          101 F(1,IF,JF,NF)=BLANK
ISN 0123              F(2,IF,JF,NF)=C
ISN 0124              F(3,IF,JF,NF)=U
ISN 0125              F(4,IF,JF,NF)=T
ISN 0126              KRAD=0
ISN 0127              GO TO 1131
ISN 0128          321 DO 331 I=1,4
ISN 0129          331 F(I,IF,JF,NF)=BLANK
ISN 0130              JRAD=0
ISN 0131              GO TO 1131
ISN 0132         1001 DO 1011 I=1,4
ISN 0133         1011 F(I,IF,JF,NF)=NEG(I)
                C
                C
                C ********************************************************************
                C
ISN 0134          131 IF(NI.NE.NN) GO TO 602
ISN 0136         1131 CALL FCIRC
                C
                C ********************************************************************
```

```
                    C
                    C
ISN 0137                IF(ISTOP.EQ.1)GO TO 61
                    C
                    C
                    C ***********************************************************************
                    C
ISN 0139                GO TO 1601
                    C
                    C ***********************************************************************
                    C
                    C
ISN 0140            261 IF(NF.LT.2)GO TO 271
                    C
                    C
                    C ***********************************************************************
                    C
                    C       WRITE DATA OF LOWEST FACTOR OF SAFETY
                    C
ISN 0142                IF(FMIN.GE.1000.) STOP
ISN 0144                WRITE(6,181)
ISN 0145            181 FORMAT('1',50X,'TRACE - SLICE DATA:',/)
ISN 0146                WRITE(6,41)(TITL(I),I=1,20)
ISN 0147                WRITE(6,191)
ISN 0148            191 FORMAT(' ','  F.OF S.MIN.    RADIUS      CENTER X     CENTER Y       L
                       1EVEL')
ISN 0149                WRITE(6,201)FMIN,RADM,CXM,CYM,ELM
ISN 0150            201 FORMAT(' ',5X,F5.2,4(5X,F7.0),/)
ISN 0151                WRITE(6,251)
ISN 0152            251 FORMAT(' ',15X,'ARC LEN.    CENTER X    CENTER Y     VERT.WT        PO
                       1RPR           TAU          TANPHI',/)
ISN 0153                IF(NNM.LE.31)GO TO 811
ISN 0155                WRITE(6,821)NNM
ISN 0156            821 FORMAT('0',10X,'NNM GREATER THAN 31, EXCEEDS LIMITS. NNM= ',I4,/,1
                       10X,'STOP PRINTOUT OF LOWEST VALUES.')
ISN 0157                GO TO 851
ISN 0158            811 DO 211  I=1,NNM
ISN 0159                WRITE(6,221)BSM(I)
ISN 0160            221 FORMAT('0',10X,'WIDTH OF SLICES: ',F8.1)
ISN 0161                WRITE(6,231)(ARCM(I,J),XBM(I,J),YBM(I,J),ACCM(I,J),PORM(I,J),TAUM(
                       1I,J),TAM(I,J), J=1,10)
ISN 0162            231 FORMAT(' ',/,10(10X,7(3X,F9.2)/))
ISN 0163                WRITE(6,241)
ISN 0164            241 FORMAT('-')
ISN 0165            211 CONTINUE
                    C
                    C
                    C ***********************************************************************
                    C
                    C       WRITE RESUME OF FACTORS OF SAFETY
                    C
ISN 0166            851 WRITE(6,571)(TITL(I),I=1,20)
ISN 0167            571 FORMAT('1',40X,'SUMMARY OF FACTORS OF SAFETY',//,40X,20A4,/)
ISN 0168                NF=NF-1
ISN 0169                DO 421 N=1,NF
ISN 0170                WRITE(6,561)CL(N)
ISN 0171            561 FORMAT(' ',30X,'TANGENTIAL LEVEL: ',F8.1,/)
ISN 0172                I12=IN12(N)
```

207

```
ISN 0173          I13=IN13(N)
ISN 0174          WRITE(6,551)(CX(I,I13,N),I=1,I12)
ISN 0175      551 FORMAT(' ',10X,'/ ',15F8.1,/)
ISN 0176          WRITE(6,401)
ISN 0177      401 FORMAT(' ',132('-')/)
ISN 0178          DO 711 J=1,I13
ISN 0179          JM1=I13-J+1
ISN 0180          WRITE(6,411)CY(1,JM1,N),((F(II,I,JM1,N),II=1,4),I=1,I12)
ISN 0181      411 FORMAT(' ',1X,F8.1,' / ',15(3X,2A1,'.',2A1),/)
ISN 0182      711 CONTINUE
ISN 0183          WRITE(6,401)
ISN 0184          WRITE(6,551)(CX(I,1,N),I=1,I12)
ISN 0185          WRITE(6,731)
ISN 0186      731 FORMAT('1')
ISN 0187      421 CONTINUE
ISN 0188      271 IF(INEXT.NE.1)GO TO 441
ISN 0190          WRITE(6,431)
ISN 0191      431 FORMAT('1',10X,'''NEXT''CARD ENCOUNTERED - START NEW EMBANKMENT.')
ISN 0192          WRITE(6,731)
ISN 0193          GO TO 21
ISN 0194      441 IF(ILAST.EQ.1)WRITE(6,451)
ISN 0196      451 FORMAT('1',10X,'''LAST'' CARD ENCOUNTERED - RUN TERMINATED.')
ISN 0197          WRITE(6,731)
ISN 0198          STOP
ISN 0199          END
```

```
LEVEL 21.8 ( JUN 74 )                    OS/360  FORTRAN H

        COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                           SOURCE,EBCDIC,NOLIST,DECK,LOAD,MAP,NOEDIT,ID,NOXREF
                   C
                   C  ******************************************************************
                   C  ******************************************************************
                   C
      ISN 0002           SUBROUTINE XSECT
                   C
                   C
                   C  ******************************************************************
                   C
                   C     SUBROUTINE XSECT - 2 - SLOAN
                   C     SUBPROGRAM TO READ AND STORE CROSS-SECTICN DATA
                   C     COMMON BLOCK TO MAIN PROGRAM AND ALL SUBRCUTINES
                   C
      ISN 0003           IMPLICIT INTEGER*2(I-N)
      ISN 0004           COMMON/BLK/CX(15,15,5),CY(15,15,5),AAC(30,10),GAMAH(30,10),ARCIN(3
                        10,10),XB(30,10),YB(30,10),UPORP(30,10),SIG(5,10),
                        2TAU(5,10),EQ(32),SQ(32),XQ(32),YQ(32),TANPHI(30,10),TAUE(30,10)
                        3,BS(30),ELQ(30),S(30),SEQ(30),X1(30),X2(30),XLC(30),XQ1(30),XQ2(30
                        4),Y1(30),Y2(30),YLC(30),YQ1(30),YSS(30)/BKI4/LSL(14)/BLK/CO(10),SP
                        5Z(10),WW(10),WS(10),XPZ1(10),XPZ2(10),YPZ1(10),CL(5)
      ISN 0005           COMMON/BKI4/LXY(5),NEG(4),L
                        6EQ(5),LPZ(4),CIRC,EQPT,LAST,LINE,NEXT,TOT,SOIL,PIEZ/BLK/FS,G
                        7,H,R,WD,IS(30),ISJC(30),IST(10)/BKI2/NM(10)/BLK/IN1
                        82(5),IN13(5)/BKI2/O,U,T,BLANK,BR,SI/BLK/IEQ,IF,ILAST,IMIN,INEXT,IP
                        9Z,IRAD,ISTOP,JF,JPAD,KRAD,NEQ,NF,NN,NPIEZ,NQ,NSOL,NXS,I,J,MM,N1
      ISN 0006           INTEGER*2 O,U,T,BLANK,F
      ISN 0007           INTEGER*4 NEXT,LAST,LINE,TOT,PIEZ,EQPT,SCIL,CIRC,LXY,LPZ,LEQ,LSL
      ISN 0008           INTEGER*4 BR,SI,DESC
                   C
                   C     DIMENSION BLOCK FOR X-SECT
                   C
      ISN 0009           DIMENSION YQ2(30),YPZ2(30)
                   C
                   C
                   C  ******************************************************************
                   C
                   C     GEOMETRY CROSS-SECTICN DATA
                   C
                   C  ******************************************************************
                   C
                   C     INITIALISE SUMMATICN CHECK VALUES
                   C
      ISN 0010           WRITE(6,5000)
      ISN 0011      5000 FORMAT(1X,'CARD NO  DESC         X1          Y1          X2          Y2
                       1    SOIL TYPE OR EQPT LEVEL')
      ISN 0012           WRITE(6,15000)
      ISN 0013     15000 FORMAT('-')
      ISN 0014           X1T=0.
      ISN 0015           Y1T=0.
      ISN 0016           X2T=0.
      ISN 0017           Y2T=0.
      ISN 0018           ISS=0
                   C
                   C
                   C     READ IN CROSS-SECTICN DATA
                   C
```

```
ISN 0019          DO 92 I=1,NXS
ISN 0020          READ(5,12)DESC,X1(I),Y1(I),X2(I),Y2(I),IS(I)
ISN 0021       12 FORMAT(A4,4F8.1,I5)
ISN 0022          WRITE(6,1002)I,DESC,X1(I),Y1(I),X2(I),Y2(I),IS(I)
ISN 0023     1002 FORMAT(1X,5X,I2,2X,A4,4(2X,F9.2),10X,I5)
              C
              C
              C         CHECK CARD HEADER
              C
ISN 0024          IF(DESC.EQ.LINE)GO TO 32
ISN 0026          WRITE(6,22)I,DESC
ISN 0027       22 FORMAT('0',10X,'HEADER OF ',I2,'TH CROSS-SECTION CARD IS INCORRECT
                 1 AND READS: ',A4,/)
ISN 0028          ISTOP=1
ISN 0029          IF(DESC.EQ.NEXT.OR.DESC.EQ.LAST)GO TO 802
              C
              C
              C         CHECK IF SOIL TYPE DEFINED
              C
ISN 0031       32 IF(IS(I).GT.0.AND.IS(I).LE.10)GO TO 52
ISN 0033          WRITE(6,42)I,IS(I)
ISN 0034       42 FORMAT('0',10X,'NO SOIL TYPE DEFINED ON ',I2,'TH CROSS-SECTION CAR
                 1D (',I5,' ), ''IS'' IS NOT WITHIN SPECIFIED LIMITS.',/)
ISN 0035          ISTOP=1
              C
              C
              C         CHECK VERTICALITY OF LINES
              C BECAUSE OF FORM Y=MX+B VERTICAL SLOPES EQUAL INFINITY
              C SLOPES SHOULD NEITHER EXCEED 100.
              C
ISN 0036       52 IF(X1(I).NE.X2(I))GO TO 72
ISN 0038          WRITE(6,62)X1(I),Y1(I),X2(I),Y2(I),I
ISN 0039       62 FORMAT('0',10X,'LINE (',F8.1,',',F8.1,'),(',F8.1,',',F8.1,') ON ',
                 1I2,'TH CROSS-SECTION CARD IS VERTICAL.',/)
ISN 0040          ISTOP=1
ISN 0041       72 S(I)=(Y2(I)-Y1(I))/(X2(I)-X1(I))
ISN 0042          IF(ABS(S(I)).GE.100.)WRITE(6,82)X1(I),Y1(I),X2(I),Y2(I),I
ISN 0044       82 FORMAT('0',10X,'SLOPE OF LINE (',F8.1,',',F8.1,'),(',F8.1,',',F8.1
                 1,') ON ',I2,'TH CROSS-SECTION CARD EXCEEDS 100.',/,10X,'SOLUTION M
                 2AY BE INCORRECT.',/)
              C
              C
              C         SUM CROSS-SECTION DATA BY COLUMNS
              C
ISN 0045          X1T=X1T+X1(I)
ISN 0046          Y1T=Y1T+Y1(I)
ISN 0047          X2T=X2T+X2(I)
ISN 0048          Y2T=Y2T+Y2(I)
ISN 0049       92 ISS=ISS+IS(I)
              C
              C
              C         READ SUM CARD
              C
ISN 0050          READ(5,12)DESC,XT1,YT1,XT2,YT2,ITS
ISN 0051          WRITE(6,11002)DESC,XT1,YT1,XT2,YT2,ITS
ISN 0052    11002 FORMAT(1X,7X,2X,A4,4(2X,F9.2),10X,I5)
              C
              C
```

```
                C       CHECK CARD HEADER
                C
ISN 0053                IF(DESC.EQ.TOT)GO TO 122
ISN 0055                WRITE(6,112)DESC
ISN 0056            112 FORMAT('0',10X,'TOTAL CARD DOES NOT FOLLOW CROSS-SECTION DATA, CAR
                       1D HEADER READS: ',A4,/)
ISN 0057                ISTOP=1
ISN 0058                IF(DESC.EQ.NEXT.OR.DESC.EQ.LAST)GO TO 802
                C
                C
                C       CHECK COLUMN TOTALS
                C
ISN 0060            122 IF(X1T.EQ.XT1)GO TO 132
ISN 0062                NCOL=1
ISN 0063                GO TO 172
ISN 0064            132 IF(Y1T.EQ.YT1)GO TO 142
ISN 0066                NCOL=2
ISN 0067                GO TO 172
ISN 0068            142 IF(X2T.EQ.XT2)GO TO 152
ISN 0070                NCOL=3
ISN 0071                GO TO 172
ISN 0072            152 IF(Y2T.EQ.YT2)GO TO 162
ISN 0074                NCOL=4
ISN 0075                GO TO 172
ISN 0076            162 IF(ISS.EQ.ITS)GO TO 192
ISN 0078                NCOL=5
ISN 0079            172 WRITE(6,182)LXY(NCOL),NCOL
ISN 0080            182 FORMAT('0',10X,A4,'CROSS-SECTION DATA COLUMN ',I2,' DOES NOT MATCH
                       1 TOTAL.',/)
ISN 0081                GO TO(132,142,152,162,192),NCOL
                C
                C
                C ***********************************************************************
                C
                C       PIEZOMETRIC SURFACE DATA
                C
ISN 0082            192 IF(NPIEZ.GT.0)GO TO 212
ISN 0084                WRITE(6,202)
ISN 0085            202 FORMAT(1X,'NO PIEZOMETRIC SURFACE DATA - NO GROUNDWATER INFLUENCE
                       1IN PRESENT PROBLEM')
ISN 0086                GO TO 562
                C
                C
                C       INITIALISE SUMMATION CHECK VALUES
                C
ISN 0087            212 X1T=0.
ISN 0088                Y1T=0.
ISN 0089                X2T=0.
ISN 0090                Y2T=0.
ISN 0091                WRITE(6,15000)
                C
                C
                C       READ IN PIEZOMETRIC DATA
                C
ISN 0092                DO 282 I=1,NPIEZ
ISN 0093                READ(5,222)DESC,XPZ1(I),YPZ1(I),XPZ2(I),YPZ2(I)
ISN 0094            222 FORMAT(A4,4F8.1)
ISN 0095                WRITE(6,2002)I,DESC,XPZ1(I),YPZ1(I),XPZ2(I),YPZ2(I)
```

```
ISN 0096        2002 FORMAT(1X,5X,I2,2X,A4,4(2X,F9.2))
                C
                C
                C        CHECK CARD HEADER
                C
ISN 0097             IF(DESC.EQ.PIEZ)GO TO 242
ISN 0099             WRITE(6,232)I,DESC
ISN 0100         232 FORMAT('0',10X,'HEADER OF ',I2,'TH PIEZOMETRIC DATA CARD IS INCORR
                    1ECT AND READS: ',A4,/)
ISN 0101             ISTOP=1
ISN 0102             IF(DESC.EQ.NEXT.OR.DESC.EQ.LAST)GO TO 802
                C
                C
                C        CHECK VERTICALITY OF LINES
                C
ISN 0104         242 IF(XPZ1(I).NE.XPZ2(I))GO TO 262
ISN 0106             WRITE(6,252)XPZ1(I),YPZ1(I),XPZ2(I),YPZ2(I),I
ISN 0107         252 FORMAT('0',10X,'LINE (',F8.1,',',F8.1,'),(',F8.1,',',F8.1,') ON ',
                    1I2,'TH PIEZOMETRIC CARD IS VERTICAL.',/)
ISN 0108             ISTOP=1
ISN 0109         262 SPZ(I)=(YPZ2(I)-YPZ1(I))/(XPZ2(I)-XPZ1(I))
ISN 0110             IF(ABS(SPZ(I)).GE.100.)WRITE(6,272)XPZ1(I),YPZ1(I),XPZ2(I),YPZ2(I)
                    1,I
ISN 0112         272 FORMAT('0',10X,'SLOPE OF PIEZOMETRIC LINE (',F8.1,',',F8.1,'),(',F
                    18.1,',',F8.1,') ON ',I2,'TH CARD EXCEEDS 100.',/,10X,'SOLUTION OF
                    2PROBLEM MAY BE INCORRECT.',/)
                C
                C
                C        SUM PIEZOMETRIC DATA COLUMNS
                C
ISN 0113             X1T=X1T+XPZ1(I)
ISN 0114             Y1T=Y1T+YPZ1(I)
ISN 0115             X2T=X2T+XPZ2(I)
ISN 0116         282 Y2T=Y2T+YPZ2(I)
                C
                C
                C        READ SUM CARD
                C        CHECK CARD HEADER
                C        CHECK COLUMN TOTALS
                C
ISN 0117             READ(5,222)DESC,XT1,YT1,XT2,YT2
ISN 0118             WRITE(6,12002)DESC, XT1,YT1,XT2,YT2
ISN 0119       12002 FORMAT(1X,7X,2X,A4,4(2X,F9.2))
ISN 0120             IF(DESC.EQ.TOT)GO TO 312
ISN 0122             WRITE(6,302)
ISN 0123         302 FORMAT('0',10X,'TOTAL CARD DOES NOT FOLLOW PIEZOMETRIC DATA, CARD
                    1HEADER READS: ',A4,/)
ISN 0124             ISTOP=1
ISN 0125             IF(DESC.EQ.NEXT.OR.DESC.EQ.LAST)GO TO 802
ISN 0127         312 IF(X1T.EQ.XT1)GO TO 322
ISN 0129             NCOL=1
ISN 0130             GO TO 352
ISN 0131         322 IF(Y1T.EQ.YT1)GO TO 332
ISN 0133             NCOL=2
ISN 0134             GO TO 352
ISN 0135         332 IF(X2T.EQ.XT2)GO TO 342
ISN 0137             NCOL=3
ISN 0138             GO TO 352
```

```
ISN 0139        342 IF(Y2T.EQ.YT2)GO TO 372
ISN 0141            NCOL=4
ISN 0142        352 WRITE(6,362)LPZ(NCOL),NCOL
ISN 0143        362 FORMAT('0',10X,A4,2X,'PIEZOMETRIC DATA COLUMN ',I2,' DOES NOT MATC
                   1H TOTAL.',/)
ISN 0144            GO TO(322,332,342,372),NCOL
              C
              C
              C ********************************************************************
              C
              C     EQUIPOTENTIAL NET DATA
              C
              C ********************************************************************
              C
              C
ISN 0145        372 IF(NEQ.GT.0)GO TO 392
ISN 0147            WRITE(6,382)
ISN 0148        382 FORMAT('0',10X,'NO EQUIPOTENTIAL DATA - SOLUTION WILL ASSUME HORIZ
                   1ONTAL FLOW',/)
ISN 0149            GO TO 562
              C
              C
              C     INITIALISE SUMMATION CHECK VALUES
              C
ISN 0150        392 X1T=0.
ISN 0151            Y1T=0.
ISN 0152            X2T=0.
ISN 0153            Y2T=0.
ISN 0154            X3T=0.
ISN 0155            WRITE(6,15000)
              C
              C
              C     READ EQUIPOTENTIAL DATA
              C     CHECK CARD HEADER
              C
ISN 0156            DO 462 I=1,NEQ
ISN 0157            READ(5,402)DESC,XQ1(I),YQ1(I),XQ2(I),YQ2(I),ELQ(I)
ISN 0158        402 FORMAT(A4,5F8.1)
ISN 0159            WRITE(6,2012)I,DESC,XQ1(I),YQ1(I),XQ2(I),YQ2(I),ELQ(I)
ISN 0160       2012 FORMAT(1X,5X,I2,2X,A4,4(2X,F9.2),7X,F9.2)
ISN 0161            IF(DESC.EQ.EQPT)GO TO 422
ISN 0163            WRITE(6,412)I,DESC
ISN 0164        412 FORMAT('0',10X,'HEADER OF ',I2,'TH EQUIPOTENTIAL DATA CARD IS INCO
                   1RRECT AND READS: ',A4,/)
ISN 0165            ISTOP=1
ISN 0166            IF(DESC.EQ.NEXT.OR.DESC.EQ.LAST)GO TO 802
              C
              C
              C     CHECK VERTICALITY OF LINES
              C
ISN 0168        422 IF(XQ1(I).NE.XQ2(I))GO TO 442
ISN 0170            WRITE(6,432)XQ1(I),YQ1(I),XQ2(I),YQ2(I),I
ISN 0171        432 FORMAT('0',10X,'LINE (',F8.1,',',F8.1,'),(',F8.1,',',F8.1,') ON ',
                   1I2,'TH EQUIPOTENTIAL CARD IS VERTICAL.',/)
ISN 0172            ISTOP=1
ISN 0173        442 SEQ(I)=(YQ2(I)-YQ1(I))/(XQ2(I)-XQ1(I))
ISN 0174            IF(ABS(SEQ(I)).GE.100.)WRITE(6,452)XQ1(I),YQ1(I),XQ2(I),YQ2(I),I
ISN 0176        452 FORMAT('0',10X,'SLOPE OF EQUIPOTENTIAL LINE (',F8.1,',',F8.1,'),('
```

213

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                          1,F8.1,'.',F8.1,') ON ',I2,'TH CARD EXCEEDS 100.',/,10X,'SOLUTION O
                          2F PROBLEM MAY BE INCORRECT.',/)
                    C
                    C
                    C      SUM EQUIPOTENTIAL DATA COLUMNS
                    C
 ISN 0177                  X1T=X1T+XQ1(I)
 ISN 0178                  Y1T=Y1T+YQ1(I)
 ISN 0179                  X2T=X2T+XQ2(I)
 ISN 0180                  Y2T=Y2T+YQ2(I)
 ISN 0181              462 X3T=X3T+ELQ(I)
                    C
                    C
                    C      READ SUM CARD
                    C      CHECK CARD HEADER
                    C      CHECK COLUMN TOTALS
                    C
 ISN 0182                  READ(5,402)DESC,XT1,YT1,XT2,YT2,XT3
 ISN 0183                  WRITE(6,12012)DESC,XT1,YT1,XT2,YT2,XT3
 ISN 0184            12012 FORMAT(1X,7X,2X,A4,4(2X,F9.2),7X,F9.2)
 ISN 0185                  IF(DESC.EQ.TOT)GO TO 492
 ISN 0187                  WRITE(6,482)DESC
 ISN 0188              482 FORMAT('0',10X,'TOTAL CARD DOES NOT FOLLOW EQUIPOTENTIAL DATA, CAR
                          1D HEADER READS: ',A4,/)
 ISN 0189                  ISTOP=1
 ISN 0190                  IF(DESC.EQ.NEXT.OR.DESC.EQ.LAST)GO TO 802
 ISN 0192              492 IF(X1T.EQ.XT1)GO TO 502
 ISN 0194                  NCOL=1
 ISN 0195                  GO TO 542
 ISN 0196              502 IF(Y1T.EQ.YT1)GO TO 512
 ISN 0198                  NCOL=2
 ISN 0199                  GO TO 542
 ISN 0200              512 IF(X2T.EQ.XT2)GO TO 522
 ISN 0202                  NCOL=3
 ISN 0203                  GO TO 542
 ISN 0204              522 IF(Y2T.EQ.YT2)GO TO 532
 ISN 0206                  NCOL=4
 ISN 0207                  GO TO 542
 ISN 0208              532 IF(X3T.EQ.XT3)GO TO 562
 ISN 0210                  NCOL=5
 ISN 0211              542 WRITE(6,552)LEQ(NCOL),NCOL
 ISN 0212              552 FORMAT('0',10X,A4,2X,'EQUIPOTENTIAL DATA COLUMN ',I2,' DOES NOT MA
                          1TCH TOTAL.',/)
 ISN 0213                  GO TO(502,512,522,532,562),NCOL
                    C
                    C
                    C *****************************************************************
                    C
                    C      SOIL PROPERTIES
                    C
                    C *****************************************************************
                    C
                    C
                    C      INITIALISE SUMMATION CHECK VALUES
                    C
 ISN 0214              562 ISS=0
 ISN 0215                  TWW=0.
 ISN 0216                  TWS=0.
```

```
ISN 0217          TC=0.
ISN 0218          X1T=0.
ISN 0219          Y1T=0.
ISN 0220          X2T=0.
ISN 0221          Y2T=0.
ISN 0222          X3T=0.
ISN 0223          Y3T=0.
ISN 0224          X4T=0.
ISN 0225          Y4T=0.
ISN 0226          X5T=0.
ISN 0227          Y5T=0.
ISN 0228          WRITE(6,15000)
ISN 0229          WRITE(6,15000)
            C
            C
            C     READ SOIL PROPERTIES DATA
            C     CHECK CARD HEADER
            C     SUM SOIL DATA BY COLUMNS
            C
ISN 0230          DO 602 I=1,NSOL
ISN 0231          READ(5,572)DESC,IST(I),WW(I),WS(I),CO(I),(SIG(J,I),TAU(J,I),J=1,5)
ISN 0232      572 FORMAT(A4,I2,13F5.1)
ISN 0233          WRITE(6,2022)I,DESC,IST(I),WW(I),WS(I),CO(I),(SIG(J,I),TAU(J,I),J=
                 11,5)
ISN 0234     2022 FORMAT(1X,5X,I2,2X,A4,2X,I2,2X,13(2X,F6.1))
ISN 0235          IF(DESC.EQ.SOIL)GO TO 592
ISN 0237          WRITE(6,582)I,DESC
ISN 0238      582 FORMAT('0',10X,'HEADER OF ',I2,'TH SOIL CARD IS INCORRECT AND READ
                 1S: ',A4,/)
ISN 0239          ISTOP=1
ISN 0240          IF(DESC.EQ.NEXT.OR.DESC.EQ.LAST)GO TO 802
ISN 0242      592 ISS=ISS+IST(I)
ISN 0243          TWW=TWW+WW(I)
ISN 0244          TWS=TWS+WS(I)
ISN 0245          TC=TC+CO(I)
ISN 0246          X1T=X1T+SIG(1,I)
ISN 0247          Y1T=Y1T+TAU(1,I)
ISN 0248          X2T=X2T+SIG(2,I)
ISN 0249          Y2T=Y2T+TAU(2,I)
ISN 0250          X3T=X3T+SIG(3,I)
ISN 0251          Y3T=Y3T+TAU(3,I)
ISN 0252          X4T=X4T+SIG(4,I)
ISN 0253          Y4T=Y4T+TAU(4,I)
ISN 0254          X5T=X5T+SIG(5,I)
ISN 0255      602 Y5T=Y5T+TAU(5,I)
            C
            C
            C     READ SUM CARD
            C     CHECK CARD HEADER
            C     CHECK COLUMN TOTALS
            C
ISN 0256          READ(5,572)DESC,ITS,WWT,WST,CT,XT1,YT1,XT2,YT2,XT3,YT3,XT4,YT4,XT5
                 1,YT5
ISN 0257          WRITE(6,12022)DESC,ITS,WWT,WST,CT,XT1,YT1,XT2,YT2,XT3,YT3,XT4,YT4,
                 1XT5,YT5
ISN 0258    12022 FORMAT(1X,7X,2X,A4,2X,I2,2X,13(2X,F6.1))
ISN 0259          IF(DESC.EQ.TOT)GO TO 632
ISN 0261          WRITE(6,622)
```

```
ISN 0262        622 FORMAT('0',10X,'TOTAL CARD DOES NOT FOLLOW SOIL DATA, CARD HEADER
                   1READS: ',A4,/)
ISN 0263            ISTOP=1
ISN 0264            IF(DESC.EQ.NEXT.OR.DESC.EQ.LAST)GO TO 802
ISN 0266        632 IF(ISS.EQ.ITS)GO TO 642
ISN 0268            NCOL=1
ISN 0269            GO TO 742
ISN 0270        642 IF(WWT.EQ.TWW)GO TO 652
ISN 0272            NCOL=2
ISN 0273            GO TO 742
ISN 0274        652 IF(WST.EQ.TWS)GO TO 662
ISN 0276            NCOL=3
ISN 0277            GO TO 742
ISN 0278        662 IF(TC.EQ.CT)GO TO 672
ISN 0280            NCOL=4
ISN 0281            GO TO 742
ISN 0282        672 IF(X1T.EQ.XT1)GO TO 682
ISN 0284            NCOL=5
ISN 0285            GO TO 742
ISN 0286        682 IF(Y1T.EQ.YT1)GO TO 692
ISN 0288            NCOL=6
ISN 0289            GO TO 742
ISN 0290        692 IF(X2T.EQ.XT2)GO TO 702
ISN 0292            NCOL=7
ISN 0293            GO TO 742
ISN 0294        702 IF(YT2.EQ.Y2T)GO TO 712
ISN 0296            NCOL=8
ISN 0297            GO TO 742
ISN 0298        712 IF(X3T.EQ.XT3)GO TO 722
ISN 0300            NCOL=9
ISN 0301            GO TO 742
ISN 0302        722 IF(YT3.EQ.Y3T)GO TO 732
ISN 0304            NCOL=10
ISN 0305            GO TO 742
ISN 0306        732 IF(XT4.EQ.X4T)GO TO 912
ISN 0308            NCOL=11
ISN 0309            GO TO 742
ISN 0310        912 IF(Y4T.EQ.YT4)GO TO 922
ISN 0312            NCOL=12
ISN 0313            GO TO 742
ISN 0314        922 IF(X4T.EQ.XT4)GO TO 93?
ISN 0316            NCOL=13
ISN 0317            GO TO 742
ISN 0318        932 IF(Y4T.EQ.YT4)GO TO 762
ISN 0320            NCOL=14
ISN 0321        742 WRITE(6,752)LSL(NCOL),NCOL
ISN 0322        752 FORMAT('0',10X,A4,2X,'SOIL DATA COLUMN ',I2,' DOES NOT MATCH TOTAL
                   1.',/)
ISN 0323            GO TO(642,652,662,672,682,692,702,712,722,732,912,922,932,762),NCO
                   1L
               C
               C
               C ***********************************************************************
               C
               C    CHECK IF INDICATED SOILS ON CROSS-SECTION CARDS ARE  ALL PRESENT
               C
ISN 0324        762 DO 792 I=1,NXS
ISN 0325            DO 772 J=1,NSOL
```

```
ISN 0326          IF(IS(I).EQ.IST(J))GO TO 792
ISN 0328      772 CONTINUE
ISN 0329          WRITE(6,782)I,IS(I)
ISN 0330      782 FORMAT('0',10X,'SOIL TYPE OF ',I2,'TH GEOMETRY CROSS-SECTION CARD
                 1(',I2,') NOT FOUND IN SOIL LIST.',/)
ISN 0331          ISTOP=1
ISN 0332      792 CONTINUE
             C
ISN 0333      802 IF(DESC.EQ.NEXT)INEXT=1
ISN 0335          IF(DESC.EQ.LAST)ILAST=1
ISN 0337          IF(ISTOP.EQ.1)WRITE(6,902)
ISN 0339      902 FORMAT('0',10X,'THIS PROBLEM WILL NOT BE EXECUTED.',/)
ISN 0340          RETURN
ISN 0341          END
```

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LEVEL 21.8 ( JUN 74 )                              OS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,DECK,LOAD,MAP,NOEDIT,ID,NOXREF
                     C
                     C ***********************************************************************
                     C ***********************************************************************
                     C
ISN 0002                   SUBROUTINE FCIRC
                     C
                     C
                     C ***********************************************************************
                     C
                     C     SUBROUTINE FCIRC - 3 - SLOAN
                     C SUBPROGRAM TO READ AND CALCULATE FAILURE CIRCLES
                     C
                     C
                     C ***********************************************************************
                     C
                     C
                     C     COMMON BLOCK TO MAIN PROGRAM AND ALL SUBROUTINES
                     C
ISN 0003                   IMPLICIT INTEGER*2(I-N)
ISN 0004                   COMMON/BLK/CX(15,15,5),CY(15,15,5),AAC(30,10),GAMAH(30,10),APCIN(3
                          10,10),XB(30,10),YB(30,10),UPORP(30,10),SIG(5,10),
                          2TAU(5,10),EQ(32),SQ(32),XQ(32),YQ(32),TANPHI(30,10),TAUE(30,10)
                          3,BS(30),ELQ(30),S(30),SEQ(30),X1(30),X2(30),XLC(30),XQ1(30),XQ2(30
                          4),Y1(30),Y2(30),YLC(30),YQ1(30),YSS(30)/BKI4/LSL(14)/BLK/CD(10),SP
                          5Z(10),WW(10),WS(10),XPZ1(10),XPZ2(10),YPZ1(10),CL(5)
ISN 0005                   COMMON/BKI4/LXY(5),NEG(4),L
                          6EQ(5),LPZ(4),CIRC,EQPT,LAST,LINE,NEXT,TOT,SOIL,PIEZ/BLK/FS,G
                          7,H,R,WD,IS(30),ISJC(30),IST(10)/BKI2/NM(10)/BLK/IN1
                          82(5),IN13(5)/BKI2/O,U,T,BLANK,BR,SI/BLK/IEQ,IF,ILAST,IMIN,INEXT,IP
                          9Z,IRAD,ISTOP,JF,JRAD,KRAD,NEQ,NF,NN,NPIEZ,NQ,NSOL,NXS,I,J,MM,N1
ISN 0006                   INTEGER*2 O,U,T,BLANK,F
ISN 0007                   INTEGER*4 NEXT,LAST,LINE,TOT,PIEZ,EQPT,SOIL,CIRC,LXY,LPZ,LEQ,LSL
ISN 0008                   INTEGER*4 BR,SI,DESC
ISN 0009                   INTEGER*4 IC,JC,I12,I13
                     C
                     C
                     C ***********************************************************************
                     C
                     C     CHECK IF FIRST  RUN THROUGH PRESENT CARD
                     C
ISN 0010                   IF(IRAD.GT.0) GO TO 43
                     C
                     C
                     C ***********************************************************************
                     C
                     C     READ FAILURE CIRCLE CARD
                     C
ISN 0012                13 NF=NF+1
ISN 0013                   READ(5,23)DESC,X1T,Y1T,X2T,Y2T,X3T,Y3T,IN12(NF),IN13(NF),CL(NF)
ISN 0014                23 FORMAT(A4,6F8.1,2I3,F8.1)
                     C
                     C
                     C ***********************************************************************
                     C
                     C     CHECK CARD HEADER
                     C
```

```
ISN 0015          IF(DESC.NE.CIRC)GO TO 63
            C
            C
            C ********************************************************************
            C
            C     DETERMINE NUMBER OF INCREMENTS
            C     DETERMINE VARIATION BETWEEN INCREMENTS
            C
ISN 0017          IF(IN12(NF).LE.0.OR.IN12(NF).GT.15) IN12(NF)=15
ISN 0019          IF(IN13(NF).LE.0.OR.IN13(NF).GT.15) IN13(NF)=15
ISN 0021          I12=IN12(NF)
ISN 0022          I13=IN13(NF)
ISN 0023          DX12=(X2T-X1T)/FLOAT(I12-1)
ISN 0024          DY12=(Y2T-Y1T)/FLOAT(I12-1)
ISN 0025          DX13=(X3T-X1T)/FLOAT(I13-1)
ISN 0026          DY13=(Y3T-Y1T)/FLOAT(I13-1)
            C
            C
            C ********************************************************************
            C
            C     CALCULATE FAILURE CIRCLES CENTERS
            C
ISN 0027          DO 33 JC=1,I13
ISN 0028          XS=X1T+FLOAT(JC-1)*DX13
ISN 0029          YS=Y1T+FLOAT(JC-1)*DY13
ISN 0030          DO 33 IC=1,I12
ISN 0031          CX(IC,JC,NF)=XS+FLOAT(IC-1)*DX12
ISN 0032       33 CY(IC,JC,NF)=YS+FLOAT(IC-1)*DY12
ISN 0033          IRAD=1
ISN 0034          IF=1
ISN 0035          JF=1
ISN 0036          H=CX(IF,JF,NF)
ISN 0037          G=CY(IF,JF,NF)
ISN 0038          RETURN
            C
            C
            C ********************************************************************
            C
            C     DETERMINE NEXT FAILURE CIRCLE FOR PROBLEM
            C
ISN 0039       43 IF=IF+1
ISN 0040          IF(IF.LE.IN12(NF))GO TO 53
ISN 0042          IF=1
ISN 0043          JF=JF+1
ISN 0044          IF(JF.GT.IN13(NF))GO TO 113
ISN 0046       53 H=CX(IF,JF,NF)
ISN 0047          G=CY(IF,JF,NF)
ISN 0048          RETURN
            C
            C
            C     CHECK IF TO MANY FAILURE CIRCLE DEFINING CARDS
            C
ISN 0049      113 IF(NF.LT.5)GO TO 13
ISN 0051          NF=NF+1
ISN 0052          READ(5,133)DESC
ISN 0053      133 FORMAT(A4)
ISN 0054          IF(DESC.NE.CIRC)GO TO 63
ISN 0056          WRITE(6,103)
```

```
      ISN 0057          103 FORMAT('0',15X,'NUMBER OF FAILURE CIRCLE CARDS EXCEEDS SPECIFIED L
                           1IMITS; ONLY THE FIRST FIVE ARE USED.',/)
      ISN 0058              ISTOP=1
      ISN 0059              RETURN
                      C
                      C
                      C ******************************************************************
                      C
                      C     NOT A CIRCLE CARD: DETERMINE IF NEXT OR LAST.
                      C
      ISN 0060           63 ISTOP=1
      ISN 0061              IF(DESC.NE.NEXT) GO TO 73
      ISN 0063              INEXT=1
      ISN 0064              RETURN
      ISN 0065           73 IF(DESC.NE.LAST) GO TO 83
      ISN 0067              ILAST=1
      ISN 0068              RETURN
      ISN 0069           83 WRITE(6,93)DESC
      ISN 0070           93 FORMAT('0',15X,'ERROR IN FAILURE CIRCLE DEFENITION CARD HEADING OR
                           1 NO LAST OR NEXT CARD, CARD HEADER READS: ',A4,/)
      ISN 0071              RETURN
      ISN 0072              END
```

```
COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                   SOURCE,EBCDIC,NOLIST,DECK,LOAD,MAP,NOEDIT,ID,NOXREF
                 C
                 C  ***************************************************************
                 C  ***************************************************************
                 C
      ISN 0002          SUBROUTINE INTER
                 C
                 C
                 C  ***************************************************************
                 C
                 C      SUBROUTINE INTER - 4 - SLOAN
                 C      SUBPROGRAM TO CALCULATE INTERSECTIONS
                 C      OF FAILURE CIRCLE AND GEOMETRY
                 C
                 C
                 C  ***************************************************************
                 C
                 C      COMMON BLOCK TO MAIN PROGRAM AND ALL SUBROUTINES
      ISN 0003          IMPLICIT INTEGER*2(I-N)
      ISN 0004          COMMON/BLK/CX(15,15,5),CY(15,15,5),AAC(30,10),GAMAH(30,10),APCIN(3
                       10,10),XB(30,10),YB(30,10),UPORP(30,10),SIG(5,10),
                       2TAU(5,10),EQ(32),SQ(32),XQ(32),YQ(32),TANPHI(30,10),TAUE(30,10)
                       3,BS(30),ELQ(30),S(30),SEQ(30),X1(30),X2(30),XLC(30),XQ1(30),XQ2(30
                       4),Y1(30),Y2(30),YLC(30),YQ1(30),YSS(30)/BKI4/LSL(14)/BLK/CO(10),SP
                       5Z(10),WW(10),WS(10),XPZ1(10),XPZ2(10),YPZ1(10),CL(5)
      ISN 0005          COMMON/BKI4/LXY(5),NEG(4),L
                       6EQ(5),LPZ(4),CIRC,EQPT,LAST,LINE,NEXT,TOT,SCIL,PIEZ/BLK/FS,G
                       7,H,R,WD,IS(30),ISJC(30),IST(10)/BKI2/NM(10)/BLK/IN1
                       82(5),IN13(5)/BKI2/O,U,T,BLANK,BR,SI/BLK/IEQ,IF,ILAST,IMIN,INEXT,IP
                       9Z,IRAD,ISTOP,JF,JRAD,KRAD,NEQ,NF,NN,NPIEZ,NQ,NSOL,NXS,I,J,MM,NI
      ISN 0006          INTEGER*2 O,U,T,BLANK,F
      ISN 0007          INTEGER*4 NEXT,LAST,LINE,TOT,PIEZ,EQPT,SCIL,CIRC,LXY,LPZ,LEQ,LSL
      ISN 0008          INTEGER*4 BR,SI
                 C
                 C
                 C  ***************************************************************
                 C
                 C      DIMENSION BLOCK FOR INTER
                 C
      ISN 0009          DIMENSION AIX(30),AIY(30),AP(30),EV(30)
                 C
                 C
                 C  ***************************************************************
                 C
                 C      INITIALISE COUNTER FOR NO OF LINES INTERSECTING FAILURE CIRCLE
                 C      DETERMINE RADIUS OF FAILURE CIRCLE
                 C
      ISN 0010          K=0
      ISN 0011          R=G-CL(NF)
                 C
                 C
                 C  ***************************************************************
                 C
                 C      CALCULATE ROOTS OF CIRCLE AND LINE
                 C
      ISN 0012          DO 84 I=1,NXS
      ISN 0013          A=S(I)**2+1.
```

```
ISN 0014          B=2.*(S(I)*(Y1(I)-S(I)*X1(I)-G)-H)
ISN 0015          C=S(I)*X1(I)*(S(I)*X1(I)-2.*Y1(I)+2.*G)+G*(G-2.*Y1(I))+H**2+Y1(I)*
                 1*2-R**2
ISN 0016          D=B**2-4.*A*C
            C
            C
            C     IF LINE CUTS CIRCLE, D WILL BE POSITIVE GREATER THAN 0
            C
ISN 0017          IF(D.LE.0.)GO TO 84
            C
            C
            C     INITIALISE COUNTER FOR EACH SIDE OF ROOT
            C
ISN 0019          KR=1
            C
            C
            C     CHECK BOTH +SQRT(D) AND -SQRT(D)
            C
ISN 0020       24 XC=(-B+SQRT(D))/(2.*A)
ISN 0021          GO TO 44
ISN 0022       34 XC=(-B-SQRT(D))/(2.*A)
ISN 0023       44 IF(ABS(X2(I)-XC).LT.0.001)GO TO 804
ISN 0025          IF(ABS(X1(I)-XC).LT.0.001) XC=X1(I)
ISN 0027          IF((X1(I)-XC)/(X2(I)-XC).GT.0.)GO TO 74
ISN 0029          GO TO 814
ISN 0030      804 XC=X2(I)
ISN 0031      814 IF(K.EQ.0)GO TO 54
ISN 0033          DO 824 J=1,K
ISN 0034          IF(ABS(AIX(J)-XC).LT.0.001)GO TO 74
ISN 0036      824 CONTINUE
ISN 0037       54 K=K+1
ISN 0038          AIX(K)=XC
ISN 0039          AIY(K)=S(I)*XC-S(I)*X1(I)+Y1(I)
ISN 0040          IF(D.LT.1.)WRITE(6,64)X1(I),Y1(I),X2(I),Y2(I),H,G,CL(NF)
ISN 0042       64 FORMAT('0',19X,'LINE (',F8.1,',',F8.1,'),(',F8.1,',',F8.1,') IS AL
                 1MOST TANGENT TO FAILURE CIRCLE (',F8.1,',',F8.1,',',F8.1,').',/)
ISN 0043       74 KR=KR+1
ISN 0044          GO TO(24,34,84),KR
ISN 0045       84 NN=1
ISN 0046          IF(K.GT.0)GO TO 834
ISN 0048          WRITE(6,94)H,G,CL(NF)
ISN 0049       94 FORMAT('0',15X,'FAILURE CIRCLE (',F8.1,',',F8.1,',',F8.1,') DOES N
                 1OT INTERSECT SLOPE.',/)
ISN 0050          KRAD=1
ISN 0051          RETURN
ISN 0052      834 IF(K.GT.1)GO TO 104
ISN 0054          WRITE(6,844)H,G,CL(NF)
ISN 0055      844 FORMAT('0',15X,'CIRCLE (',F8.1,',',F8.1,',',F8.1,') ONLY INTERSECT
                 1S SLOPE AT ONE POINT: EXTENT OF GEOMETRY INSUFFICIENT.',/,15X,'STO
                 2P EXECUTION OF THIS CIRCLE.',/)
ISN 0056          JRAD=1
ISN 0057          RETURN
            C
            C
            C     PUT INTERSECTIONS IN ORDER ACCORDING TO DECREASING X VALUE
            C
ISN 0058      104 AX=-9400.
ISN 0059      114 DO 144 I=1,K
```

```
ISN 0060          IF(AX-AIX(I))134,124,144
ISN 0061      124 AIX(I)=-9500.
ISN 0062          GO TO 104
ISN 0063      134 AX=AIX(I)
ISN 0064          AY=AIY(I)
ISN 0065      144 CONTINUE
ISN 0066          XLC(NN)=AX
ISN 0067          YLC(NN)=AY
ISN 0068          NN=NN+1
ISN 0069          IF(NN.LE.K)GO TO 114
ISN 0071          IF(NPIEZ.GT.0)GO TO 434
ISN 0073          IPZ=1
ISN 0074          RETURN
            C
            C
            C ***********************************************************************
            C
            C         CALCULATE INTERSECTIONS OF CIRCLE AND PIEZOMETRIC SURFACE
            C
            C
ISN 0075      434 K=0
ISN 0076          DO 234 I=1,NPIEZ
ISN 0077          A=SPZ(I)**2+1.
ISN 0078          B=2.*(SPZ(I)*(YPZ1(I)-SPZ(I)*XPZ1(I)-G)-H)
ISN 0079          C=SPZ(I)*XPZ1(I)*(SPZ(I)*XPZ1(I)-2.*YPZ1(I)+2.*G)+G*(G-2.*YPZ1(I))
                 1+H**2+YPZ1(I)**2-R**2
ISN 0080          D=B**2-4.*A*C
ISN 0081          IF(D.LE.0.)GO TO 234
ISN 0083          KR=1
ISN 0084      184 XC=(-B+SQRT(D))/(2.*A)
ISN 0085          GO TO 204
ISN 0086      194 XC=(-B-SQRT(D))/(2.*A)
ISN 0087      204 IF(ABS(XPZ2(I)-XC).LT.0.001)GO TO 214
ISN 0089          IF(ABS(XPZ1(I)-XC).LT.0.001) XC=XPZ1(I)
ISN 0091          IF((XPZ1(I)-XC)/(XPZ2(I)-XC).GT.0.)GO TO 224
ISN 0093          GO TO 504
ISN 0094      214 XC=XPZ2(I)
ISN 0095      504 IF(K.EQ.0) GO TO 514
ISN 0097          DO 524 J=1,K
ISN 0098          IF(ABS(AIX(J)-XC).LT.0.001) GO TO 224
ISN 0100      524 CONTINUE
ISN 0101      514 K=K+1
ISN 0102          AIX(K)=XC
ISN 0103          AIY(K)=SPZ(I)*XC-SPZ(I)*XPZ1(I)+YPZ1(I)
ISN 0104      224 KR=KR+1
ISN 0105          GO TO(184,194,234),KR
ISN 0106      234 CONTINUE
            C
            C
            C         CHECK IF CIRCLE CUTS PIEZOMETRIC SURFACE
            C
ISN 0107          IF(K.GT.1)GO TO 444
ISN 0109          IPZ=1
ISN 0110          WRITE(6,454)H,G,CL(NF)
ISN 0111      454 FORMAT('0',19X,'FAILURE CIRCLE (',F8.1,',',F8.1,',',F8.1,') DOES N
                 1OT INTERSECT PIEZOMETRIC SURFACE: NO POREPRESSURE INFLUENCE.',/)
ISN 0112          RETURN
            C
```

```
                  C
                  C     CHECK EXTENSION OF PIEZOMETRIC GEOMETRY
                  C     TO COVER PRESENT FAILURE CIRCLE
                  C
      ISN 0113     444 KI=K/2
      ISN 0114         K2=KI*2
      ISN 0115         IF(K2.EQ.K)GO TO 494
      ISN 0117         JRAD=1
      ISN 0118         WRITE(6,484)H,G,CL(NF)
      ISN 0119     484 FORMAT('0',15X,'PIEZOMETRIC SURFACE DOES NOT EXTEND TO COVER (',F8
                      1.1,',',F8.1,',',F8.1,') FAILURE CIRCLE.',/,15X,'STOP EXECUTION OF
                      2THIS CIRCLE.',/)
      ISN 0120         RETURN
                  C
                  C
                  C     DETERMINE FIRST AND LAST INTERSECTION ALONG PIEZOMETRIC SURFACE
                  C
      ISN 0121     494 XQ(1)=-9400.
      ISN 0122         XPP=10000.
      ISN 0123         DO 254 I=1,K
      ISN 0124         IF(AIX(I).LE.XQ(1))GO TO 244
      ISN 0126         XQ(1)=AIX(I)
      ISN 0127         YQ(1)=AIY(I)
      ISN 0128         EQ(1)=AIY(I)
      ISN 0129     244 IF(AIX(I).GE.XPP)GO TO 254
      ISN 0131         XPP=AIX(I)
      ISN 0132         YPP=AIY(I)
      ISN 0133     254 CONTINUE
                  C
                  C
                  C ****************************************************************
                  C
                  C     CALCULATE INTERSECTIONS OF CIRCLE AND EQUIPOTENTIAL LINES
                  C
                  C
      ISN 0134         K=0
      ISN 0135         IF(NEQ.GT.0)GO TO 284
      ISN 0137         IEQ=1
      ISN 0138         RETURN
      ISN 0139     284 DO 344 I=1,NEQ
      ISN 0140         A=SEQ(I)**2+1.
      ISN 0141         B=2.*(SEQ(I)*(YQ1(I)-SEQ(I)*XQ1(I)-G)-H)
      ISN 0142         C=SEQ(I)*XQ1(I)*(SEQ(I)*XQ1(I)-2.*YQ1(I)+2.*G)+G*(G-2.*YQ1(I))+H*
                      1*2+YQ1(I)**2-R**2
      ISN 0143         D=B**2-4.*A*C
      ISN 0144         IF(D.LE.0.)GO TO 344
      ISN 0146         KR=1
      ISN 0147     294 XC=(-B+SQRT(D))/(2.*A)
      ISN 0148         GO TO 314
      ISN 0149     304 XC=(-B-SQRT(D))/(2.*A)
      ISN 0150     314 IF(ABS(XQ2(I)-XC).LT.0.001)GO TO 324
      ISN 0152         IF(ABS(XQ1(I)-XC).LT.0.001) XC=XQ1(I)
      ISN 0154         IF((XQ1(I)-XC)/(XQ2(I)-XC).GT.0.)GO TO 334
      ISN 0156         IF(XC.GE.XQ(1).OR.XC.LE.XPP)GO TO 334
      ISN 0158         GO TO 534
      ISN 0159     324 XC=XQ2(I)
      ISN 0160     534 IF(K.EQ.0) GO TO 544
      ISN 0162         DO 554 J=1,K
```

```
ISN 0163          IF(ABS(AIX(J)-XC).LT.0.001) GO TO 334
ISN 0165      554 CONTINUE
ISN 0166      544 K=K+1
ISN 0167          AIX(K)=XC
ISN 0168          AIY(K)=SEQ(I)*XC-SLQ(I)*XQ1(I)+YQ1(I)
ISN 0169          EV(K)=ELQ(I)
ISN 0170          AP(K)=SEQ(I)
ISN 0171      334 KR=KR+1
ISN 0172          GO TO(294,304,344),KR
ISN 0173      344 CONTINUE
              C
              C
              C   PUT CIRCLE-EQUIPOTENTIALS IN DECREASING ORDER
              C   FIRST AND LAST ARE INTERSECTIONS WITH PIEZOMETRIC SURFACE
              C
ISN 0174          XQ(K+2)=XPP
ISN 0175          YQ(K+2)=YPP
ISN 0176          EQ(K+2)=YPP
ISN 0177          IF(K.GT.0)GO TO 604
ISN 0179          IEQ=1
ISN 0180          RETURN
ISN 0181      604 NQ=2
ISN 0182      354 AX=-9400.
ISN 0183      364 DO 394 I=1,K
ISN 0184          IF(AX-AIX(I)) 384,374,394
ISN 0185      374 AIX(I)=-9500.
ISN 0186          GO TO 354
ISN 0187      384 AX=AIX(I)
ISN 0188          AY=AIY(I)
ISN 0189          EL=EV(I)
ISN 0190          AI=AP(I)
ISN 0191      394 CONTINUE
ISN 0192          XQ(NQ)=AX
ISN 0193          YQ(NQ)=AY
ISN 0194          EQ(NQ)=EL
ISN 0195          SQ(NQ)=AI
ISN 0196          NQ=NQ+1
ISN 0197          IF(NQ.LE.(K+1))GO TO 364
ISN 0199          NQ=NQ-1
ISN 0200          SQ(1)=SQ(2)
ISN 0201          SQ(NQ+1)=SQ(NQ)
ISN 0202          RETURN
ISN 0203          END
```

```
      LEVEL 21.8 ( JUN 74 )                          OS/360  FORTRAN H

            COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                               SOURCE,EBCDIC,NOLIST,DECK,LOAD,MAP,NOEDIT,ID,NOXREF
                     C
                     C  ************************************************************************
                     C  ************************************************************************
                     C
      ISN 0002             SUBROUTINE FOFS
                     C
                     C
                     C  ************************************************************************
                     C
                     C     SUBROUTINE FOFS - 5 - SLOAN
                     C     SUBPROGRAM TO CALCULATE FACTOR OF SAFETY
                     C     COMMON BLOCK TO MAIN PROGRAM AND ALL SUBROUTINES
                     C
      ISN 0003             IMPLICIT INTEGER*2(I-N)
      ISN 0004             COMMON/BLK/CX(15,15,5),CY(15,15,5),AAC(30,10),GAMAH(30,10),ARCIN(3
                          10,10),XB(30,10),YB(30,10),UPORP(30,10),SIG(5,10),
                          2TAU(5,10),EQ(32),SQ(32),XQ(32),YQ(32),TANPHI(30,10),TAUE(30,10)
                          3,BS(30),ELQ(30),S(30),SEQ(30),X1(30),X2(30),XLC(30),XQ1(30),XQ2(30
                          4),Y1(30),Y2(30),YLC(30),YQ1(30),YSS(30)/BKI4/LSL(14)/BLK/CO(10),SP
                          5Z(10),WW(10),WS(10),XPZ1(10),XPZ2(10),YPZ1(10),CL(5)
      ISN 0005             COMMON/BKI4/LXY(5),NEG(4),L
                          6EQ(5),LPZ(4),CIRC,EQPT,LAST,LINE,NEXT,TOT,SOIL,PIEZ/BLK/FS,G
                          7,H,R,WD,IS(30),ISJC(30),IST(10)/BKI2/NM(10)/BLK/IN1
                          82(5),IN13(5)/BKI2/O,U,T,BLANK,BR,SI/BLK/IEQ,IF,ILAST,IMIN,INEXT,IP
                          9Z,IRAD,ISTOP,JF,JRAD,KRAD,NEQ,NF,NN,NPIEZ,NQ,NSOL,NXS,I,J,MM,N1
      ISN 0006             INTEGER*2 O,U,T,BLANK,F
      ISN 0007             INTEGER*4 NEXT,LAST,LINE,TOT,PIEZ,EQPT,SOIL,CIRC,LXY,LPZ,LEQ,LSL
      ISN 0008             INTEGER*4 BR,SI
                     C
                     C     DIMENSION BLOCK FOR FOFS
                     C
      ISN 0009             DIMENSION P1(300),P2(300),IUJC(30),YST(30)
      ISN 0010             DIMENSION FX(2),FY(2)
                     C
                     C  ************************************************************************
                     C
                     C     INITIALISE CONTROL FOR REORDERING XLC OF MULTIPLE FAILURE SURFACE
      ISN 0011             IC=0
                     C
                     C     CHECK IF MULTIPLE FAILURE SURFACE
      ISN 0012             IF(NN.EQ.N1) GO TO 525
                     C
                     C     MODIFY XLC MATRIX TO ANALYSE NEXT PART OF FALURE SURFACE
      ISN 0014         505 IC=IC+1
      ISN 0015             XLC(IC)=XLC(N1+IC+1)
      ISN 0016             IF((N1+IC).LE.NN) GO TO 505
      ISN 0018             NN=NN-N1+1
      ISN 0019             GO TO 515
                     C
                     C
                     C     INITIALISE VALUES
                     C
                     C     NN = NO OF GROUPS OF SLICES
      ISN 0020         525 NN=NN-2
                     C     ISLC = SLICE NO
      ISN 0021         515 ISLC=1
```

```
             C      ARC = TOTAL LENGTH OF FAILURE ARC
ISN 0022            ARC=0.
             C      TTSS = TOTAL SHEAR STRESS
ISN 0023            TTSS=0.
             C      TTNES = TOTAL EFFECTIVE STRESS
ISN 0024            TTNES=0.
             C
             C
             C ************************************************************************
             C
             C      FOR EACH PAIR OF INTERSECTING POINTS ALONG THE BASE
             C      OF A FAILURE CIRCLE.
             C
             C      N1 = NO OF SLICES IN ANALYSED PART OF MULTIPLE FAILURE SURFACE
ISN 0025            N1=NN
ISN 0026            DO 155 I=1,NN
             C
             C
             C      DETERMINE WIDTH OF SLICES BETWEEN TWO INTERSECTIONS
             C      (10 SLICES EACH)
             C
ISN 0027            BS(I)=(XLC(I)-XLC(I+1))*0.1
             C
             C
             C      FOR EACH OF 10 SLICES BETWEEN TWO INTERSECTIONS
             C      DETERMINE COORDINATE OF CENTER OF BASE OF SLICE
             C
ISN 0028            XBI=XLC(I)-BS(I)*0.5
ISN 0029            DO 155 J=1,10
             C
             C
             C      DETERMINE AND STORE COORDINATES OF CENTER OF BASE OF SLICE.
             C
ISN 0030            XB(I,J)=XBI
ISN 0031            YB(I,J)=G-SQRT(ABS(R**2-(H-XB(I,J))**2))
             C
             C
             C      DETERMINE LENGHT OF ARC AT BASE OF SLICE
             C
ISN 0032            XAM=XB(I,J)-0.5*BS(I)
ISN 0033            XAP=XB(I,J)+0.5*BS(I)
ISN 0034            YAP=G-SQRT(ABS(R**2-(H-XAP)**2))
ISN 0035            YAM=G-SQRT(ABS(R**2-(H-XAM)**2))
             C      ARCIN = ARC LENGTH OF SLICE BASE
ISN 0036            ARCIN(I,J)=R*2.*ARSIN((SQRT((XAM-XAP)**2+(YAM-YAP)**2))/(2*R))
ISN 0037            ARC=ARC+ARCIN(I,J)
             C
             C
             C      DETERMINE GEOMETRY LINES CUT BY VERTICAL SLICE
             C
             C      K = NO OF GEOMETRY LINES CUT BY SLICE ABOVE BASE
ISN 0038            K=0
ISN 0039            DO 55 L=1,NXS
ISN 0040            IF(X2(L).EQ.XB(I,J)) GO TO 15
ISN 0042            IF((X1(L)-XB(I,J))/(X2(L)-XB(I,J)).GT.0.) GO TO 55
             C
             C
             C      DETERMINE YS, Y COORDINATE OF INTERSECTION OF XB AND GEOMETRY LINE
```

227

```
                         C      DETERMINE IF YS IS ABOVE OR BELOW FAILURE SURFACE, STORE YS.
                         C
                         C      YS = ELEVATION OF VERTICAL LINE XB AND GEOMETRY LINE
      ISN 0044              15  YS= S(L)*(XB(I,J)-X1(L))+Y1(L)
      ISN 0045                  IF(YS.LE.YB(I,J)) GO TO 55
      ISN 0047                  K=K+1
                         C      YST = STORED VALUE OF YS
      ISN 0048                  YST(K)=YS
                         C
                         C
                         C      DETERMINE SOIL PROPERTIES AT INTERSECTION
                         C
      ISN 0049                  JCNT=0
      ISN 0050                  DO 25 ICNT=1,NSCL
      ISN 0051                  JCNT=JCNT+1
      ISN 0052                  IF(IS(L).EQ.IST(JCNT)) GO TO 45
      ISN 0054              25  CONTINUE
      ISN 0055                  WRITE(6,35)IS(L),X1(L),Y1(L),X2(L),Y2(L),L
      ISN 0056              35  FORMAT('0',15X,'SOIL TYPE ',I2,' UNDER LINE (',F8.1,',',F8.1,'),('
                              1,F8.1,',',F8.1,') ON ',I2,'TH CROSS-SECTION CARD CAN''T BE FOUND F
                              2OR SLICE CALCULATION.',/,15X,'STOP EXECUTION OF THIS CIRCLE.',/)
      ISN 0057                  JRAD=1
      ISN 0058                  RETURN
                         C      IUJC = STORED SOIL TYPE AT INTERSECTION OF SLICE AND GEOMETRY
      ISN 0059              45  IUJC(K)=JCNT
      ISN 0060              55  MM=1
                         C
                         C
                         C      DETERMINE IF CIRCLE CUTS SLOPE SURFACE BETWEEN ENTRY AND EXIT POINTS.
                         C      IF K=0, NO SOIL ABOVE BASE OF SLICE... BASE OF SLICE ABOVE SURFACE
                         C
      ISN 0061                  IF(K.GT.0.OR.IC.GT.0) GO TO 65
      ISN 0063                  N1=I-1
      ISN 0064                  WRITE(6,405)H,G,CL(NF), XLC(1),XLC(N1)
      ISN 0065             405  FORMAT('0',15X,'FAILURE CIRCLE (',F8.1,',',F8.1,',',F8.1,') CUTS S
                              1LOPE AT MORE THAN ONE FAILURE SURFACE.',/,15X,'PROGRAM WILL ANALYS
                              2E EACH SEPERATE PORTION.',/,15X,'X FROM ',F8.1,' TO ', F8.1,' .')
      ISN 0066                  IF(N1.GT.0)GO TO 415
      ISN 0068                  JRAD=1
      ISN 0069                  RETURN
                         C
                         C
                         C      PUT GEOMETRY¬SLICE INTERSECTIONS IN DECREASING Y ORDER
                         C
      ISN 0070              65  AYY=-9400.
      ISN 0071              75  DO 105 M=1,K
      ISN 0072                  IF(AYY-YST(M)) 95,85,105
      ISN 0073              85  YST(M)=-9500.
      ISN 0074                  GO TO 65
      ISN 0075              95  AYY=YST(M)
      ISN 0076                  IJC=IUJC(M)
      ISN 0077             105  CONTINUE
      ISN 0078                  YSS(MM)=AYY
      ISN 0079                  ISJC(MM)=IJC
      ISN 0080                  MM=MM+1
      ISN 0081                  IF(MM.LE.K) GO TO 75
      ISN 0083                  YSS(MM)=YB(I,J)
      ISN 0084                  ISJC(MM)=ISJC(MM-1)
```

```
ISN 0085          IF((YSS(1)-YSS(MM)).GE.ABS((Y1(1)-Y2(NXS))*0.02))KRAD=0
              C
              C *************************************************************************
              C       INITIALISE SUBROUTINE WEIGTH VALUES
              C
              C
ISN 0087          GAMAH(I,J)=0.
ISN 0088          UPORP(I,J)=0.
              C
              C
              C *************************************************************************
              C
ISN 0089          CALL WEIGHT
              C
              C *************************************************************************
              C
              C
ISN 0090          IF(JRAD.EQ.1)RETURN
              C
              C
              C       IF METRIC SYSTEM IS USED, CHANGE CALCULATED WEIGHT INTO STRESS.
              C
ISN 0092          IF(WD-1.0.GT.0.001)GO TO 425
ISN 0094          GAMAH(I,J)=GAMAH(I,J)*0.0098
ISN 0095          UPORP(I,J)=UPORP(I,J)*9.8
              C
              C
              C       DETERMINE COHESION AND PHI FROM EFFECTIVE STRESS
              C       ACTING ON BASE OF SLICE.
              C
ISN 0096      425 COSAL=(G-YB(I,J))/R
ISN 0097          SINAL=(H-XB(I,J))/R
ISN 0098          IF(YLC(1).GT.YLC(NN+1)) SINAL=-SINAL
ISN 0100          EUS=GAMAH(I,J)-UPORP(I,J)
ISN 0101          IF(EUS.GE.0.) GO TO 905
ISN 0103          WRITE(6,915) EUS, ISLC
ISN 0104      915 FORMAT(' ', 15X,'EFFECTIVE UNIT STRESS VALUE LESS THAN ZERO ( ',F8
                 1.1,' )',/,16X,'AND HAS BEEN REAJUSTED TO ZERO FOR THE FOLLOWING FA
                 2ILURE CIRCLE SLICE NO: ',I3,' .')
ISN 0105          EUS=0.
ISN 0106      905 IF(EUS.GT.0.) GO TO 1905
ISN 0108          TAUE(I,J)=CO(ISJC(MM))
ISN 0109          TANPHI(I,J)=(TAU(1,ISJC(MM))-CO(ISJC(MM)))/SIG(1,ISJC(MM))
ISN 0110          GO TO 1235
              C
              C
              C       DETERMINE THE EFFECTIVE SHEAR STRENGTH CORRESPONDING TO THE
              C          COMPUTED EFFECTIVE NORMAL STRESS
              C
ISN 0111     1905 JNC=0
ISN 0112          DO 115 JN=1,5
ISN 0113          JNC=JNC+1
ISN 0114          IF(EUS.LE.SIG(JN,ISJC(MM))) GO TO 125
ISN 0116          IF(JN.EQ.5) GO TO 135
ISN 0118          IF(SIG(JN+1,ISJC(MM)).EQ.0.) GO TO 125
ISN 0120      115 CONTINUE
ISN 0121      125 IF(JNC.GT.1) GO TO 135
ISN 0123          TANPHI(I,J)=(TAU(1,ISJC(MM))-CO(ISJC(MM)))/SIG(1,ISJC(MM))
```

```
ISN 0124             GO TO 235
ISN 0125         135 TANPHI(I,J)=(TAU(JNC,ISJC(MM))-TAU(JNC-1,ISJC(MM)))/(SIG(JNC,ISJC(
                    1MM))-SIG(JNC-1,ISJC(MM)))
ISN 0126         235 TAUE(I,J)=TAU(JNC,ISJC(MM))+(TANPHI(I,J)*(EUS-SIG(JNC,ISJC(MM))))
               C
               C
               C ***********************************************************************
               C
               C     CALCULATE PARTS OF BISHOP EQUATION
               C
ISN 0127        1235 P1(ISLC)=TAUE(I,J)*ARCIN(I,J)
ISN 0128             P2(ISLC)=TANPHI(I,J)*ABS(SINAL/COSAL)
ISN 0129             TTSS=TTSS+GAMAH(I,J)*SINAL*ABS(BS(I))
               C
               C
               C     DO NEXT SLICE
               C
ISN 0130             XBI=XB(I,J)-BS(I)
ISN 0131         155 ISLC=ISLC+1
               C
               C
               C ***********************************************************************
               C
               C     CALCULATE FACTOR OF SAFETY
               C
ISN 0132         415 NSLC=N1*10
ISN 0133             IF(KRAD.EQ.1) RETURN
ISN 0135             F0=2.0
ISN 0136        1415 INF=0
ISN 0137        1005 FNCT=0.
ISN 0138             DO 175 ISLC=1,NSLC
ISN 0139         175 FNCT=FNCT+(P1(ISLC)/(1+(P2(ISLC)/F0)))
ISN 0140             FS=FNCT/TTSS
ISN 0141             IF(ABS(FS-F0).LE.0.005) GO TO 205
ISN 0143             INF=INF+1
ISN 0144             FX(INF)=F0
ISN 0145             FY(INF)=FS
ISN 0146             F0=FS
ISN 0147             IF(INF.EQ.2) GO TO 1015
ISN 0149             GO TO 1005
ISN 0150        1015 SLF=(FY(2)-FY(1))/(FX(2)-FX(1))
ISN 0151             IF((1.-SLF).LT.0.001) GO TO 1205
ISN 0153             F0=(FY(1)-(SLF*FX(1)))/(1.-SLF)
ISN 0154             GO TO 1415
ISN 0155         205 WRITE(6,215)FS,H,G,CL(NF),TTSS,ARC
ISN 0156         215 FORMAT(' ',19X,F6.3,3F10.2,1X,1F11.0,4X,F9.2)
ISN 0157             RETURN
ISN 0158        1205 WRITE(6,195) H,G,CL(NF)
ISN 0159         195 FORMAT('0',15X,'NO CONVERGENCE OF THE FACTOR OF SAFETY OF CIRCLE (
                    1',F8.1,',',F8.1,',',F8.1,').')
ISN 0160             JRAD=1
ISN 0161             RETURN
ISN 0162             END
```

```
          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,DECK,LOAD,MAP,NOEDIT,ID,NOXREF
                  C
                  C ********************************************************************
                  C ********************************************************************
                  C
ISN 0002                SUBROUTINE WEIGHT
                  C
                  C
                  C ********************************************************************
                  C
                  C     SUBROUTINE WEIGHT - 6 - SLOAN
                  C     SUBPROGRAM TO CALCULATE POREPRESSURE AND WEIGHT
                  C     COMMON BLOCK TO MAIN PROGRAM AND ALL SUBROUTINES
                  C
ISN 0003                IMPLICIT INTEGER*2(I-N)
ISN 0004                COMMON/BLK/CX(15,15,5),CY(15,15,5),AAC(30,10),GAMAH(30,10),ARCIN(3
                       10,10),XB(30,10),YB(30,10),UPORP(30,10),SIG(5,10),
                       2TAU(5,10),EQ(32),S)(32),XQ(32),YQ(32),TANPHI(30,10),TAUE(30,10)
                       3,BS(30),ELQ(30),S(30),SEQ(30),X1(30),X2(30),XLC(30),XQ1(30),XQ2(30
                       4),Y1(30),Y2(30),YLC(30),YQ1(30),YSS(30)/BKI4/LSL(14)/BLK/CO(10),SP
                       5Z(10),WW(10),WS(10),XPZ1(10),XPZ2(10),YPZ1(10),CL(5)
ISN 0005                COMMON/BKI4/LXY(5),NEG(4),L
                       6EQ(5),LPZ(4),CIRC,EQPT,LAST,LINE,NEXT,TOT,SOIL,PIEZ/BLK/FS,G
                       7,H,R,WD,IS(30),ISJC(30),IST(10)/BKI2/NM(10)/BLK/IN1
                       82(5),IN13(5)/BKI2/O,U,T,BLANK,BR,SI/BLK/IEQ,IF,ILAST,IMIN,INEXT,IP
                       9Z,IRAD,ISTOP,JF,JRAD,KPAD,NEQ,NF,NN,NPIEZ,NQ,NSOL,NXS,I,J,MM,N1
ISN 0006                INTEGER*2 O,U,T,BLANK,F
ISN 0007                INTEGEP*4 NEXT,LAST,LINE,TOT,PIEZ,EQPT,SOIL,CIRC,LXY,LPZ,LEG,LSL
ISN 0008                INTEGER*4 BR,SI
                  C
                  C
                  C ********************************************************************
                  C
                  C     CALCULATE WEIGHT OF SLICE
                  C
                  C     IF NO PIEZOMETRICSURFACE, NO GROUNDWATER INFLUENCE -GAMMA WET ONLY
                  C
ISN 0009                KG=MN-1
ISN 0010                IF(IPZ.NE.1)GO TO 26
                  C
                  C
                  C     CALCULATE TOT. WT. OF SLICE FROM WET DENSITY ONLY
                  C
ISN 0012                DO 16 JN=1,KG
ISN 0013             16 GAMAH(I,J)=GAMAH(I,J)+WW(ISJC(JN))*(YSS(JN)-YSS(JN+1))
ISN 0014                RETURN
                  C
                  C
                  C     CALCULATE TOT. WT. FROM BOTH SOIL AND PIEZOMETRIC DATA
                  C     DETERMINE WHICH PIEZOMETRIC IS CUT BY SLICE
                  C
ISN 0015             26 DO 36 II=1,NPIEZ
ISN 0016                IZ=II
ISN 0017                IF(ABS(XPZ2(IZ)-XB(I,J)).LT.0.001) GO TO 56
ISN 0019                IF(ABS(XPZ1(IZ)-XB(I,J)).LT.0.001) GO TO 56
ISN 0021                IF((XPZ1(IZ)-XB(I,J))/(XPZ2(IZ)-XB(I,J)).LT.0.) GO TO 56
ISN 0023             36 CONTINUE
```

231

```
      ISN 0024          WRITE(6,46) H,G,CL(NF)
      ISN 0025       46 FORMAT('_',15X,'PIEZOMETRIC SURFACE DOES NOT EXTEND TO COVER PRESE
                       1NT PROBLEM.',/,15X,'FAILURE CIRCLE (',F8.1,',',F8.1,',',F8.1,') WI
                       2LL NOT BE EXECUTED.',/)
      ISN 0026          JRAD=1
      ISN 0027          RETURN
                  C
                  C
                  C     DETERMINE INTERSECTION OF PIEZOMETRIC LINE AND SLICE CENTER
                  C
      ISN 0028       56 YXB=YPZ1(IZ)+SPZ(IZ)*(XB(I,J)-XPZ1(IZ))
                  C
                  C
                  C     DETERMINE POSITION OF SLICE-GEOM. INTERSECT. TO PIEZ. SURFACE
                  C     CALCULATE WEIGHT OF WATER OVERLYING SOIL.
                  C
      ISN 0029          IF(YSS(1).LT.YXB)GAMAH(I,J)=(YXB-YSS(1))*WD
      ISN 0031          DO 86 JN=1,KG
      ISN 0032          IF(YSS(JN).GT.YXB) GO TO 66
                  C
                  C
                  C     ALL OF SLICE BELOW PIEZOMETRIC SURFACE
                  C
      ISN 0034          GAMAH(I,J)=GAMAH(I,J)+WS(ISJC(JN))*(YSS(JN)-YSS(JN+1))
      ISN 0035          GO TO 86
                  C
                  C
                  C     TOP OF SLICE ABOVE PIEZOMETRIC SURFACE
                  C
      ISN 0036       66 IF(YSS(JN+1).GE.YXB) GO TO 76
                  C
                  C
                  C     PIEZOMETRIC SURFACE CUTS THROUGH SLICE
                  C
      ISN 0038          GAMAH(I,J)=GAMAH(I,J)+WW(ISJC(JN))*(YSS(JN)-YXB)+WS(ISJC(JN))*(YXB
                       1-YSS(JN+1))
      ISN 0039          GO TO 86
                  C
                  C
                  C     ALL OF SLICE ELEMENT ABOVE PIEZOMETRIC SURFACE
                  C
      ISN 0040       76 GAMAH(I,J)=GAMAH(I,J)+WW(ISJC(JN))*(YSS(JN)-YSS(JN+1))
      ISN 0041       86 CONTINUE
                  C
                  C
                  C ******************************************************************
                  C
                  C     CALCULATE POREPRESSURE
                  C
      ISN 0042          IF(IEQ.NE.1)GO TO 96
                  C
                  C
                  C     NO EQUIPOTENTIAL LINES
                  C     POREPRESSURE GIVEN BY VERTICAL TO PIEZOMETRIC SURFACE.
                  C
      ISN 0044          IF(YSS(MM).LT.YXP)GO TO 205
      ISN 0046          RETURN
                  C
```

```
                        C
                        C      CALCULATE POREPRESSURE FROM VERTICAL EQUIPOTENTIALS
                        C
   ISN 0047         206 UPORP(I,J)=(YXB-YSS(MM))*WD
   ISN 0048             RETURN
                        C
                        C
                        C      POREPRESSURE CALCULATED FROM EQUIPOTENTIAL LINES
                        C      LOCATE EQUIPOTENTIAL INTERSECTIONS
                        C      ON CIRCLE DEFINING BASE OF SLICE
                        C
   ISN 0049          96 JN=0
   ISN 0050             DO 106 II=1,NQ
   ISN 0051             JN=JN+1
   ISN 0052             IF(ABS(XQ(JN+1)-XB(I,J)).LT.0.001) GO TO 126
   ISN 0054             IF(ABS(XQ(JN)-XB(I,J)).LT.0.001) GO TO 126
   ISN 0056             IF((XQ(JN)-XB(I,J))/(XQ(JN+1)-XB(I,J)).LT.0.) GO TO 126
   ISN 0058         106 CONTINUE
   ISN 0059             RETURN
                        C
                        C
                        C      CALCULATE DISTANCE OF XB,YB TO BOTH LINES
                        C
   ISN 0060         126 DIST1=ABS((YB(I,J)-YQ(JN)+SQ(JN)*(XQ(JN)-XB(I,J)))/SQRT(SQ(JN)**2+
                          11.))
   ISN 0061             DIST2=ABS((YB(I,J)-YQ(JN+1)+SQ(JN+1)*(XQ(JN+1)-XB(I,J)))/SQRT(SQ(J
                          1N+1)**2+1.))
   ISN 0062             RT=DIST1/(DIST1+DIST2)
   ISN 0063             DLY=EQ(JN)-EQ(JN+1)
   ISN 0064             UPORP(I,J)=(EQ(JN)-(RT*DLY)-YSS(MM))*WD
   ISN 0065             RETURN
   ISN 0066             END
```

```
         COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                            SOURCE,EBCDIC,NOLIST,DECK,LOAD,MAP,NOEDIT,ID,NOXREF
                   C
                   C *****************************************************************
                   C *****************************************************************
                   C
  ISN 0002                BLOCK DATA
                   C
                   C
                   C *****************************************************************
                   C
                   C       SUBROUTINE BLOCK DATA - 7 - SLOAN
                   C       BLOCK DATA TO INITIALISE VALUES
                   C       COMMON BLOCK TO MAIN PROGRAM AND ALL SUBROUTINES
                   C
  ISN 0003                IMPLICIT INTEGER*2(I-N)
  ISN 0004                COMMON/BLK/CX(15,15,5),CY(15,15,5),AAC(30,10),GAMAH(30,10),ARCIN(3
                         10,10),XB(30,10),YB(30,10),UPORP(30,10),SIG(5,10),
                         2TAU(5,10),EQ(32),SQ(32),XQ(32),YQ(32),TANPHI(30,10),TAUE(30,10)
                         3,BS(30),LLQ(30),S(30),SEQ(30),X1(30),X2(30),XLC(30),XQ1(30),XQ2(30
                         4),Y1(30),Y2(30),YLC(30),YQ1(30),YSS(30)/BKI4/LSL(14)/BLK/CO(10),SP
                         5Z(10),WW(10),WS(10),XPZ1(10),XPZ2(10),YPZ1(10),CL(5)
  ISN 0005                COMMON/BKI4/LXY(5),NEG(4),L
                         6EQ(5),LPZ(4),CIRC,EQPT,LAST,LINE,NEXT,TOT,SOIL,PIEZ/BLK/FS,C
                         7,H,R,WD,IS(30),ISJC(30),IST(10)/BKI2/NM(10)/BLK/IN1
                         82(5),IN13(5)/BKI2/O,U,T,BLANK,BR,SI/BLK/IEQ,IF,ILAST,IMIN,INEXT,IP
                         9Z,IRAD,ISTOP,JF,JFAD,KRAD,NEQ,NF,NN,NPIEZ,NQ,NSOL,NXS,I,J,MM,N1
  ISN 0006                INTEGER*2 O,U,T,BLANK,F
  ISN 0007                INTEGER*2 NEG
  ISN 0008                INTEGER*4 NEXT,LAST,LINE,TOT,PIEZ,EQPT,SOIL,CIRC,LXY,LPZ,LEQ,LSL
  ISN 0009                INTEGER*4 BR,SI
                   C
                   C
                   C *****************************************************************
                   C
                   C       DATA INITIALIZATION
                   C
  ISN 0010                DATA NEXT/'NEXT'/,LAST/'LAST'/,LINE/'LINE'/,TOT/'TOT'/,PIEZ/'PIEZ'
                         1/,EQPT/'EQPT'/,SOIL/'SOIL'/,CIRC/'CIRC'/,LXY/'X1','Y1','X2','Y2','
                         2SOIL'/,LPZ/'XPZ1','YPZ1','XPZ2','YPZ2'/,LSL/'IST','WW','WS','CO','
                         3SIG1','TAU1','SIG2','TAU2','SIG3','TAU3','SIG4','TAU4','SIG5','TAU
                         45'/,LEQ/'XEQ1','YEQ1','XEQ2','YEQ2','EQLV'/
  ISN 0011                DATA NM/'1','2','3','4','5','6','7','8','9','0'/
  ISN 0012                DATA O/'O'/,U/'U'/,T/'T'/,BLANK/' '/
  ISN 0013                DATA BR/'BR'/,SI/'SI'/
  ISN 0014                DATA NEG/' ','N','E','G'/
  ISN 0015                END
```

Appendix C

LIST OF VARIABLES USED IN FORTRAN VERSION

LIST OF VARIABLES

name	size	location	description
A		INTER	$=m^2+1$, part of the $AX^2+BX+C=$ form of the quadratic equation used to resolve the intersection of a circle and a line.
ACC	30,10	FOFS Main	=GAMAH, stored value of the total unit stress acting at the base of the slice.
ACCM	30,10	Main	=ACC, the total weight of the slice of material in the geometry showing the lowest factor of safety.
AI		INTER	=AP (I), the slope of the equipotential line; this variable is used to put the intersections of circles and equipotential lines in decreasing X-value order.
AIY	30	INTER	$=m \cdot X_C - m \cdot X1 + Y1$, Y-coordinate of a circle-line intersection.
AIX	30	INTER	$=X_C$, X-coordinate of a circle-line intersection.
Ap	30	INTER	=SEQ(30), slope of equipotential line; used to put the intersections of circles and equipotential lines in decreasing X-coordinate order.
ARC		FOFS	=ARC+ARCIN(I,J), total length of failure arc; initialised at 0.
ARCIN	30,10	FOFS Main	arc length of base of slice
ARCM	30,10	Main	arc length of base of slice of failure geometry showing the lowest factor of safety, = ARCIN(I,J).
AX		INTER	maximum X value of circle-line intersections found in scan; used to put intersections in decreasing X value order; initialised at -9400.
AY		INTER	Y-coordinate corresponding to the the maximum X value of circle-lines intersections found in scan; used

		to put intersections in order according to decreasing X value.
AYY	FOFS	Y-coordinate of slice-geometry intersections used as an intermediate step to put these in decreasing order.

B		INTER		=2(m(Y1-m·X1-G)-H), part of the $AX^2+BX+C=0$ form of the quadratic equation used to resolve the intersection of circles and lines.
BLANK		Data	Main	data variable, = 'b̸'.
BR		Data	Main	data variable used to define british system of units, ='BR'.
BS	30	FOFS	Main	=(XLC(I)-XLC(I+1))*0.1, slice width used to calculate the factor of safety.
BSM	30	Main		=BS, width of slices of the geometry showing the lowest factor of safety.

C		INTER		$=m*X1*(m*X1-2Y1+2G)+G*(G-2*Y1)+H^2+Y1^2-R^2$, portion of the $AX^2+BX+C=0$ form of the quadratic equation used to resolve the intersections of circles and lines.
CL	5	INTER	Main FOFS	tangent level of failure circle on failure circle data card.
CO	10	XSECT	FOFS	cohesion or τ' intercept of the Mohr-Coulomb envelope describing the soil shear strength on soil data cards (column 4).
COSAL		FOFS		= cosine alpha, where alpha is the angle from vertical of the line uniting the center of the base of the slice and the center of the failure circle.
CT		XSECT		sum of the τ' intercepts of the Mohr-Coulomb envelope, column 4 on the soil data cards, compared with the sum indicated on total card as an input check.
CX	15,15,5	FCIRC	Main	stored X-coordinate of failure circles center (failure circle grid points).
CXM		Main		=H, X-coordinate of center of failure circle generating the lowest calculated factor of safety.
CY	15,15,5	FCIRC	Main	stored Y-coordinate of failure circle centers (failure circle grid points).
CYM		Main		=G, Y-coordinate of center of failure circle generating the lowest calculated factor of safety.

D	INTER	$=B^2-4*A*C$, discriminant of the roots of the $AX^2-BX-C=0$ form of the quadratic equation used to resolve the intersections of circles and lines.
DESC	Main XSECT FCIRC	variable used to read and compare alphanumerics on data cards: BR or SI in Main, LINE, PIEZ, EQPT, SOIL, CIRC, NEXT or LAST in XSECT, FCIRC or Main
DIST1	WEIGHT	normal distance of center of base of slice to nearest equipotential line, EQPT line greater than center of slice.
DIST2	WEIGHT	normal distance of center of base of slice / to nearest equipotential line having an X value less than the center.
DLY	WEIGHT	difference in potential elevations of the two nearest equipotential lines of the center of the base of the slice.
DX12	CIRC	horizontal distance between increments from points one to two on failure circle grid.
DX13	CIRC	horizontal distance between increments from points one to three on failure circle grid.
DY12	CIRC	vertical distance between increments from points one to two on failure circle grid.
DY13	CIRC	vertical distance between increments from points one to three on failure circle grid.

EL		INTER	=EV(30), potential elevation of the equipotential line used to put intersections of circle and equipotential lines in decreasing X order.
ELM		Main	=CL(NF), tangential level of failure circle generating the lowest calculated factor of safety.
ELQ	30	XSECT INTER	potential elevation of the equipotential line; corresponds to the elevation of the intersection of the equipotential line and the piezometric surface; column 5 on the EQPT data cards.
EQ	32	INTER WEIGHT	stored potential elevation at the intersection of a failure circle and an equipotential line; intersections ordered according to decreasing X value.
EUS		FOFS	=ABS(GAMAH*COSAL)-UPORP, effective unit stress acting normal to the base of the slice.
EV	30	INTER	=ELQ(30), variable used to put intersections of circles and equipotential lines in decreasing X value order; potential elevation of equipotential line.

F	4,15,15,5	Main	mattrix used to store alphanumeric factors of safety in a grid corresponding to the coordinates of the centers of the failure circles.
FMIN		Main	=FS, minimum factor of safety greater than zero calculated from a set of data; initialised at zero.
FNCT		FOFS	=FNCT+(P1(ISLC)/(1+(P2/FO))), function used for summing the numerator of the Bishop modified equation.
FO		FOFS	initial assumed factor of safety value used in computing FS.
FS		FOFS Main	Calculated factor of safety.
FX	2	FOFS	X-coordinate of the FO vs FS relationship; corresponds to the assumed value used in the computation of FS (FO).
FY	2	FOFS	Y-coordinate of the FO vs FS relationship to the computed value (FS) in the computation of the factor of safety.

G	FCIRC FOFS Main	Y-coordinate of the center of the failure circle being used in computed the factor of safety.
GAMAH	WEIGHT FOFS	total unit weight of soil acting on base of slice.

H	FCIRC	FOFS Main	X-coordinate of the center of the failure circle being used un computing the factor of safety.

I12		CIRC		=1N12(5), number of increments between points one and two of the failure surface grid.
I13		CIRC		=1N13(5), number of increments between points one and three of the failure surface grid.
IC		FOFS		tracer to determine if analysing other than first part of a multiple failure surface; used to a reorder XLC for other than first part of failure surface.
IEQ		Main	INTER	control, =0 failure surface cuts equipotential lines and porewater pressure is calculated from flownet, =1 failure surface does not cut EQPT lines and porewater pressure is assumed from groundwater horizontal flow.
If		FCIRC		counter for grid increments of failure circles from points one to two.
IJC		FOFS		soil type at slice-geometry intersection; used as an intermediate step to put intersections in decreasing Y order.
ILAST		Main	XSECT FCIRC	control; =0 continue; =1 'LAST' card encountered: print out data for present run and sign off.
IN	4	Main		variable used as an intermediate step to store factors of safety alphanumeric values according to the failure circle centers coordinate grid.
IN12	5	FCIRC	Main	number of increments between points one ans two of grid on failure circle date card.
IN13	5	FCIRC	Main	number of increments between points one and three of grid on failure circle data card.
INEXT		Main	XSECT FCIRC	control; =0 continue; =1 'NEXT' card encountered, print out data

				for present run and reinitialise program for next run.
IPZ		Main	INTER WEIGHT	control; =0 failure surface cuts piezometric surface, porewater pressure influence; =1 failure surface does not cut piezometric surface, no porewater pressure influence.
IRAD		Main	FCIRC	control; =0 read a new radius card, if none end run, =1 continue with present radius card.
IS	30	XSECT	INTER FOFS	soil type below geometry line on 'LINE' card (column 5); specified limits 1 to 10 inclusive.
ISJC	30	FOFS	WEIGHT	soil type at ordered intersection of slice and geometry line.
ISLC		FOFS		slice number analysed in FOFS; initialised at one.
IST	10	XSECT	FOFS	soil type number on soil data card (column 1); specified limits from 1 to 10 inclusive.
ISTOP		Main	XSECT FCIRC	control; =0 continue; =1 stop execution of present run due to input error.
ISS		XSECT		sum of soil types on 'LINE' cards (column 5) and of soil type number on 'SOIL' cards (column 1).
ITS		XSECT		sum of soil types below geometry lines and of soil numbers as indicated on the 'TOTAL' cards following 'LINE' and 'SOIL' data cards respectively.
IUJC	30	FOFS		stored soil type at the intersection of the center of the slice and the soil geometry lines.
IZ		WEIGHT		=II, counter for piezometric line data (to go outside a doo-loop).

JNCT	FOFS	soil type at intersection of center of slice and geometry line; stored as IUJC(30).
JF	FCIRC	counter for grid increments from points one to three.
JN	WEIGHT FOFS	counter to determine between which circle-equipotentail line intersection falls center of base of slice (WEIGHT), and between which set of $\sigma_n'\cdot\tau'$ points falls the computed effective unit stress (FOFS).
JRAD	Main INTER WEIGHT FOFS	control; =0 continue; =1 abnormality encountered at execution level with present data set, bypass rest of program and start a new failure circle.

K	INTER FOFS	counter for number of geometry lines intersecting failure circle (INTER) and slice (FOFS).
K2	INTER	=KI*2, KI=F/2, K2=K if K is an even number; used to determine if the piezometric surface extends to cover failure circle.
KG	WEIGHT	=MM-1, number of intersections of center line of slice and of geometry lines above the base of the slice.
KI	INTER	=K/2, number of circle-piezometric surface intersections divided by two; used to determine if piezometric surface extends to cover failure circle.
KR	INTER	counter to determine if both roots of the quadratic equation have been examined.
KRAD	Main INTER	control; =0 comtinue; =1 failure circle does not intersect slope, bypass rest of program, print message and start a new failure circle.

LAST		Main	DATA XSECT FCIRC	data variable used to compare alphanumerics indicating end of data set.
LEQ	5	XSECT	Data	data variable used in error message to indicate in which equipotential data column a sum error has been encountered.
LPZ	4	XSECT	Data	data variable used in error message to indicate the code name of the piezometric data column in which a sum error has been encountered.
LSL	14	XSECT	Data	data variable used in error message to indicate the code name of the soil data column in which a sum error has been encountered.
LXY	5	XSECT	Data	data variable used in error message to indicate the code name of the line data column in which a sum error has been encountered.

MF	FOFS		=(FY(2)-FY(1))/(FX(2)-FX(1)), slope of the FO va FS linear relationship.
MM	FOFS	WEIGHT	counter for number of slice-geometry intersections; initialised at 0.

N1		FOFS	Main	= NN if only one failure surface is generated from a circle; number of circle-geometry intersection; used to modify NN if two or more failure surfaces per defined circle.
NCOL		XSECT		number of column where error has been encountered in summing data cards.
NEQ		Main	XSECT INTER	number of equipotential line cards as given on field definition card.
NEXT		Main	Data XSECT FCIRC	data variable used to compare alphanumeric codes indicating that a new data set follows.
NEG	4	Main	Data	data variable ='b', 'N', 'E', 'G' used to indicate a negative factor of safety in printing the factor of safety mattrix.
NF		Main	FCIRC	counter for radius cards, initialised at 0.
NM	10	Main	Data	data variable equal from 1 to 0; used to store alphanumerics in F(4,15,15,5).
NN		INTER	FOFS Main	=NN-2(FOFS). = number of circle-lines intersections +1.
NNM		Main		=NN, number of intervals between circle-lines intersections in the geometry of the lowest calculated factor of safety.
NPIEZ		Main	XSECT INTER WEIGHT	number of piezometric surface cards as given on field definition card.
NQ		INTER	WEIGHT	number of circle-equipotential lines intersections.
NSLC		FOFS		number of slices in final computation of the factor of safety.
NSOL		Main	XSECT FOFS	number of soil data cards as given on the field definition card.
NXS		Main	XSECT INTER FOFS	number of cross-section cards as given on the field definition card.

O	Main Data	data variable = 'O'.

P1	30	FOFS		=TAUE(I,J)*ARCIN(I,J), part one of the modified Bishop equation used to sum and compute FS.
P2	30	FOFS		=SINAL*TANPHI(I,J)/COSAL, part two of the modified Bishop equation used to sum and compute FS.
PORM	30,10	Main		=PORPR, porewater pressure acting at the base of the slice of the geometry showing the lowest factor of safety.
PORPR		FOFS	Main	=UPORP, unit porewater pressure acting at the base of the slice.

R	FOFS Main	=G-CL(NF), radius of failure circle.
RADM	Main	=R, radius of failure circle generating the lowest computed factor of safety.
RT	WEIGHT	=DIST1/(DIST1+DIST2), ratio of the distance from the center of the base of slice to the nearest equipotential lines.

S	30	XSECT	INTER FOFS	slope of the cross-section geometry line.
SEQ	30	XSECT	INTER	slope of equipotential lines.
SI		Main	Data	data variable used to define international system of units.
SIG	5,10	XSECT	FOFS	σ_n' coordinate of the inflexion points defining the Mohr envelope of the soil shear strength on the soil data cards.
SINAL		FOFS		sine alpha, sine of the angle from vertical of the line passing through the center of the base of the slice and the failure circle center.
SPZ	10	XSECT	INTER WEIGHT	slope of piezometric surface line.
SQ	32	INTER	WEIGHT	=AI, slope of geometry line at circle-line ordered intersections.

T		Main	Data	data variable = 'T'.
TAM	30,10	Main		=TANPHI(I,J), tangent to the Mohr-Coulomb failure envelope at the effective stress acting on the base of the slice for circle showing the lowest computed factor of safety.
TANPHI	30,10	FOFS	MAIN	slope of the line defining the soil shear strength.
TAU	5,10	XSECT	FOFS	τ' coordinate of the inflexion points defining the segments of the Mohr-Coulomb envelope describing the soil shear strength on the soil data cards.
TAUE	30,10	FOFS	Main	soil effective shear strength computed from the Mohr-Coulomg envelope and the effective normal stress.
TAUM	30,10	Main		=TAUE(I,J), effective shear strength of soil at base of slice for the circle showing the lowest factor of safety.
TC		XSECT		sum of the τ'-intercept of the soil strength envelope (column 4) on the soil data cards.
TITL	20	Main		problem title as written on title card.
TNES		FOFS	Main	=EUS*ARCIN(I,J), total normal effective stress acting on base of slice.
TNESM	30,10	Main		=TNES(I,J), total normal effective stress acting on the base of the slice of the geometry showing the lowest computed factor of safety.
TTNES		FOFS		=TTNES+TNES, initialised at 0; total normal effective stress acting on failure surface.
TTSS		FOFS		=TTSS+TSS, initialised at 0; total shear stress along failure surface.

TWS	XSECT	sum of soil saturated density (colomn 3) on soil data cards
TWW	XSECT	sum of soil wet density (column 2) on soil data cards.

U	Main	Data	data variable = 'U'.
UPORP	FOFS	WEIGHT	unit porewater pressure acting along base of slice.

WD		Main	WEIGHT	water density, =1 if DESC=SI, = 62.4 if DESC=BR.
WS	10	XSECT	WEIGHT	soil saturated density on soil data card (column 3).
WST		XSECT		sum of soil saturated densities (column 3) as given on soil TOTAL card.
WW	10	XSECT	WEIGHT	soil wet density (column 2) on soil data cards.
WWT		XSECT		sum of soil wet densities (column 2) as given on the soil TOTAL card.

X1	30	XSECT	INTER FOFS	first X-coordinate of geometry line on cross-section card (column 1).
X2	30	XSECT	INTER FOFS	second X-coordinate of geometry line of cross-section card (column 3)
X1T		XSECT FCIRC		sum of first X-coordinate (column 1) of geometry line on cross-section line cards, piezometric data cards, equipotential data cards, piezometric data, and of σ_n' (column 5) in soil data; first X-coordinate (column 1) of grid defined on failure circle data cards.
X2T		XSECT FCIRC		sum of second X-coordinate (column 3) as in X1T above, and of $\sigma_n'^2$(column 7) in soil data; second X-codinate (column 7) of grid defined on circle data cards.
X3T		XSECT FCIRC		sum of potential elevation of equipotential line (column 5) on equipotential data card, and of $\sigma_n'^3$in soil data; third X-coordinate (column 9) of grid defined on circle data cards.
X4T		XSECT		sum of $\sigma_n'^4$(column 11) on soil data cards.
X5T		XSECT		sum of $\sigma_n'^5$(column 13) on soil data cards.
XAM		FOFS		=XB(I,J)-0.5*BS(I), X-coordinate of the extremity of the base of the slice farthest from origin; used to calculate the arc length of the base of the slice.
XAP		FOFS		=XB(I,J)-0.5*BS(I), X-coordinate of the extremity of the base of the slice closest to the origin; used to calculate the arc length of the base of the slice.
XB	30,10	FOFS	Main WEIGHT FOFS	X-coordinate of the center of the base of the slice.

XBI		FOFS		=XLC(I)-BS(I)*0.5 for first computation, =XBI+BS(I) for all other computations of a same geometry; X-coordinate of the center of a slice used as an intermediate step to store same.
XBM		Main		=XB, X-coordinate of the centre of the base of the slice for the geomtery showing the lowest factor of safety.
XC		INTER		=-B±$\sqrt{D}$, roots of the quadratic equation used to resolve the intersections of a circle and a line.
XLC	30	INTER	FOFS	X-coordinate of ordered intersections of a circle and geometry lines.
XPP		INTER		X-coordinate of the intersection of a circle and piezometruc lines having the lowest X value (last when ordered).
XPZ1	10	XSECT	INTER WEIGHT	first X-coordinate of the piezometric line on the piezometric data card (column 1).
XPZ2	10	XSECT	INTER WEIGHT	second X-coordinate of the piezometric on the piezometric data card (column 3)
XQ	32	INTER	WEIGHT	X-coordinate of ordered intersections of a circle and equipotential lines.
XQ1	30	XSECT	INTER	first X-coordinate of an equipotential line on the equipotential data card (column 1).
XQ2	30	XSECT	INTER	second X-coordinate of an equipotential line on the equipotential data card (column 3).
XS		CIRC		X-coordinate of increment steps from points one to three of the failure circle grid.
XT1		XSECT		sum of X1 values (column 1) as given on TOTAL card LINE, PIEZ and

		EQPT data, and for σ_n'1 (column 5) for soil data.
XT2	XSECT	sum of X2 values (column 3) as given on TOTAL card for LINE, PIEZ and EQPT data and for σ_n'2 (column 7) for soil data.
XT3	XSECT	sum of potential elevation of equipotential lines (column 5) and of σ_n'3 (column 9) of soil data as given on TOTAL cards.
XT4	XSECT	sum of σ_n'4 (column 11) of soil data as given on the TOTAL card.
XT5	XSECT	sum of σ_n'5 (column 13) of soil data as given on the TOTAL card.

Y1	30	XSECT	INTER FOFS	first Y-coordinate of the geometry line on the cross-section cards (column 2).
Y2	30	XSECT	INTER	second Y-coordinate of the geometry line on the cross-section cards (column 4).
Y1T		XSECT FCIRC		sum of the Y 1-coo-dinate (column 2) of the geometry on LINE, PIEZ and EQPT data, and of τ'1 of SOIL data (column 6); first Y-coordinate of the grid defined on circle data.
Y2T		XSECT FCIRC		sum of the Y2-coordinate (column 4) of the geometry on LINE, PIEZ and EQPT data, and of τ'2 of SOIL data (column 8); second Y-coordinate (column 4) of the grid defined on circle cards.
Y3T		XSECT FCIRC		sum of the τ'3 (column 10) of SOIL data and third Y-coordinate (column 6) of the grid defined on circle cards.
Y4T		XSECT		sum of the τ'4 (column 12) of SOIL data.
Y5T		XSECT		sum of the τ'5 (column 14) of SOIL data.
YAM		FOFS		$=G-\sqrt{\|\|R^2-(H-XAM)^2\|\|}$, Y-coordinate of the extremity of the base of the slice farthest from origin; used to calculate the arc length of the base of the slice.
YAP		FOFS		$=G-\sqrt{\|\|R^2-(H-XAM)^2\|\|}$, Y-coordinate of the extremity of the base of the slice closest to the origin; used to calculate the arc length of the base of the slice.
YB	30,10	FOFS	Main	Y-coordinate of the center of the base of the slice.
YBM		Main		=YB, Y-coordinate of center of base of slice for the geometry showing the lowest factor of safety.

YLC	30	INTER	FOFS	Y-coordinate of ordered intersections of a circle and lines.
YPP		INTER		Y-coordinate of the intersections of a circle and piezometric lines having the lowest X value (ordered last).
YPZ1	10	XSECT	INTER WEIGHT	first Y-coordinate of line on the piezometric data card (column 2).
YPZ2	10	XSECT		second Y-coordinate of the line on the piezometric data card (column 4).
YQ	32	INTER	WEIGHT	Y-coordinate of the ordered intersections of a circle and equipotential lines.
YQ1	30	XSECT	INTER	first Y-coordinate of line on the equipotential data card (column 2).
YQ2	30	XSECT		second Y-coordinate of line on the equipotential data card (column 4).
YS		FCIRC FOFS		Y-coordinate of increments from points, ont to three of failure circle grid and of the intersection of the slice and the geometry line (to determine if intersection is above slice).
YSS	30	FOFS		Y-coordinate of ordered slice-line intersection.
YST	30	FOFS		stored value of YS, Y-coordinate of intersection of center of slice and geometry.
YT1		XSECT		sum of Y1 values (column 2) for LINE, PIEZ and EQPT data, and of τ'1 (column 6) for SOIL data, as given on the TOTAL card.
YT2		XSECT		sum of Y2 values (column 4) for LINE, PIEZ and EQPT data, and of τ'2 (column 8) for SOIL data, as given on the TOTAL card.
YT3		XSECT		sum of τ'3 (column 10) of SOIL data. as given on the TOTAL card.

YT4	XSECT	sum of τ'4 (column 12) of SOIL data, as given on the TOTAL card.
YT5	XSECT	sum of τ'5 (column 14) of SOIL data, as given on the TOTAL card.
YXB	WEIGHT	Y-coordinate of intersections of piezometric lines and slice.

Appendix D

LIST OF MESSAGES IN FORTRAN VERSION

"SLOPE STABILITY ANALYSIS - BISHOP'S MODIFIED METHOD OF SLICES" MAIN, line 13, format 11.

"problem title"

Main, line 24, format 41

writes out on data sheet problem title card, according to data variable TITL(20) on a 20A4 format.

"NUMBER OF CROSS-SECTION CARDS NXS (15) IS NOT WITHIN SPECIFIED LIMITS".

Main, line 31, format 301

Causes program interruption after scan of field definition card.

"NUMBER OF SOIL CARDS NSOL (15) IS NOT WITHIN SPECIFIED LIMITS".

Main, line 36, format 541.

Causes program interruption after scan of field definition card.

"NUMBER OF PIEZOMETRIC CARDS NPIEZ(IA) IS NOT WITHIN SPECIFIED LIMITS."

Main, line 41, format 901.

Causes program interruption after scan of field definition card.

"NUMBER OF EQUIPOTENTIAL CARDS NEQ (15) IS NOT WITHIN SPECIFIED LIMITS."

Main, line 44, format 911.

Causes program interruption after scan of field definition card.

"INTERNATIONAL OR BRITISH SYSTEM NOT SPECIFIED ON FIELD DEFINITION CARD, SYSTEM DEFINED READS; A2"

Main, line 45, format 501

Causes program interruption.

"NO PIEZOMETRIC SURFACE DATA - NO GROUDWATER INFLUENCE IN PRESENT PROBLEM."

XSECT, line 77, format 202.

No porewater pressure influence in present analysis because NPIEZ calue is zero or negative.

"NO EQUIPOTENTIAL DATA - SOLUTION WILL ASSUME HORIZONTAL FLOW".

XSECT, line 135, format 382.

No flow net influence in present problem because NEQ value is zero or negative.

"HEADER OF 12 TH EQUIPOTENTIAL DATA CARD IS INCORRECT AND READS: A4".

XSECT, line 148, format 412.

Header of equipotential card specified is not "EPQT"
Correct header or NEQ value.
Causes program interruption after scanning of rest of data.

"LINE (F8.1, F8.1), F8.1, F8.) ON 12 TH EQUIPOTENTIAL CARD IS VERTICAL".

XSECT, line 155, format 432.

The specified line is vertical. The slope of the line is equal to infitiny. The solution of the problem is indeterminate due to the Y=mX - b form of the linear equation. Redraw geometry with non vertical lines (maximum slope = 100).

"SLOPE OF EQUIPOTENTIAL LINE (F8.1, F8.1), (F8.1, F8.1) on 12 TH CARD EXCEEDS 100. SOLUTION OF PROBLEM MAY BE INCORRECT."

XSECT, line 160, format 452.

Slope of specified equipotential line is greater than allowable by the precision of the program and system.
Redraw equipotential line with a flatter slope.
No program interruption.

"TOTAL CARD DOES NOT FOLLOW EQUIPOTENTIAL DATA, CARD HEADER READS: A4"

XSECT, line 170, format 482.

An incorrect header code has been encountered on the "TOTAL" card that should follow the equipotential data.
Change to correct header, use correct NEQ value, or put cards in order.
Causes program interruption after scanning of rest of data.

"HEADER OF 12 TH CROSS-SECTION CARD IS INCORRECT AND READS: A4."

XSECT, line 21, format 22.

Header of cross-section geometry card is not "LINE".
Correct header or NXS value.
Causes program interruption after data scanning.

"NO SOIL TYPE DEFINED ON 12 TH CROSS-SECTION CARD (I5), "IS" IS NOT WITHIN SPECIFIED LIMITS."

XSECT, line 28, format 42.

The value of "IS" is either less or equal to 0, or greater than 10; spécified range is from 1 to 10 inclusively.
Correct value on cross-section geometry card and on soil data card to a value within the specified range.

Causes program interruption after scanning of data.

"SLOPE OF LINE (F8.1, F8.1), (F8.1, F8.1) ON 12 TH CROSS-SECTION CARDS EXCEEDS 100. SOLUTION MAY BE INCORRECT."

XSECT, line 38, format 82.

Slope of cross-section geometru line is greater than allowable by the precision of the program and system.
Redraw line of geometry with a flatter slope.
No program interruption.

"TOTAL CARD DOES NOT FOLLOW CROSS-SECTION DATA' CARD HEADER READS: A4".

XSECT, line 48, format 112.

An incorrect header code has been encountered on the "TOTAL" card that should follow the cross-section data.
Change to correct header, use correct NXS value, or put cards in order.
Causes program interruption after data scanning.

"A4 EQUIPOTENTIAL DATA COLUMN 12 DOES NOT MATCH TOTAL".

XSECT, line 194, format 552.

The value on the TOTAL card for the specified column is not equal to the sum of values on the equipotential cards for that column.

A value mispunched by one space is a common error.

"HEADER OF 12 TH SOIL CARD IS INCORRECT AND READS: A4".

XSECT, line 216, format 582.

The header of the soil data card is not soil.
Correct header or NSOL value on field definition card.
Causes interruption of program after scanning of rest of data.

"A4 SOIL DATA COLUMN 12 DOES NOT MATCH TOTAL'"

XSECT, line 296, format 752.

The value on the TOTAL card is not equal to the sum of values on the soil data cards for the specified column.
Check values and sum.
Mispunching of a value by one space is a common error.

"CROSS-SECTION DATA COLUMN 12 DOES NOT MATCH TOTAL".

XSECT, line 72, format 182.

Value on TOTAL card for column 12 is not equal to the sum of values on LINE cards for that column.
A value mispunched by one space in a column is a common error.

"HEADER OF 12 TH PIEZOMETRIC DATA CARD IS INCORRECT AND READS: A4".

XSECT, line 89, format 232.

The header of the piezometric data card is not PIEZ.
Correct header or PIEZ value on field definition card.
Causes interruption of program after scanning of data.

"SLOPE OF PIEZOMETRIC LINE (F8,1, F8.1), (F8.1, F8.1) ON 12TH CARD EXCEEDS 100. SOLUTION OF PROBLEM MAY BE INCORRECT."

XSECT, line 101, format 272.

The slope of the specified piezometric line is greater than allowable by the precision of the program and system.
Redraw piezometric line with a flatter slope.
No program interruption.

"LINE (F8.1, F8.1), (F8.1, F8.1) on 12 TH CROSS-SECTION CARD IS VERTICAL."

XSECT, line 33, format 62.

The specified line is vertical. The slope of the line is equal to infinity. The solution of the problem is indeterminate due to Y = mX + b form the linear equation.
Redraw geometry with no vertical lines (maximum slope = 100).

"LINE (F8.1, F8.1), (F8.10, F8.1) on 12 TH PIEZOMETRIC CARD IS VERTICAL".

XSECT, line 96, format 252.

The specified line is vertical. The slope of the line is equal to inficity. The solution of the problem is indeterminate due to Y=mX - b form of the linear equation. Redraw geometry with no vertical lines (maximum slope= 100).

"A4 PIEZOMETRIC DATA COLUMN 12 DOES NOT MATCH TOTAL."

XSECT, line 130, format 362.

The value on the total card is not equal to the sum of values on the piezometric data for the column specified. Check value and sum
Mispunching of a value by one space is a common error.

"SOIL TYPE OF 12 TH GEOMETRY CORSS-SECTION CARD (12) NOT FOUND IN SOIL LIST".

XSECT, line 306, format 782.

The soil type indicated on the specified cross-section geometry card is not in the soil data.
Check soil type specified.

"THIS PROBLEM WILL NOT BE EXECUTED."

XSECT, line 315, format 902

An error causing program interruption has been encountered.

"ERROR IN FAILURE CIRCLE DEFINITION CARD HEADING OR NO LAST OR NEXT CARD, CARD HEADER READS: A4"

FCIRC, line 70, format 93.

Header of card following the soil TOTAL card is neither CIRC, NEXT or LAST.

Check data file.
May be caused by either no CIRC cards or misplaced CIRC cards;
Execution interrupted; no data printout

"NUMBER OF FAILURE CIRCLE CARDS EXCEEDS SPECIFIED LIMITS: ONLY THE FIRST FIVE ARE USED."

FCIRC, line 57, format 103.

Number of failure circle definition cards is greater than five.
Only the first five cards will be used in the analysis.
Caused by program memory restrictions.

"PIEZOMETRIC SURFACE DOES NOT EXTEND TO COVER (F8.1, F8.1, F8.1) FAILURE CIRCLE." "STOP EXECUTION OF THIS CRICLE."

INTER, line 109, format 484.

The specified failure circle intersects the piezometric surface at an uneven number of points.
The piezometric surface does nos cover the extent of the failure circle.
The program will analyse the next failure circle.

"FAILURE CIRCLE (F8.1, F8.1, F8.1) DOES NOT INTERSECT PIEZOMETRIC SURFACE: NO POREWATER PRESSURE INFLUENCE.

INTER, line 101, format 454.

The failure circle does not intersect any of the segments defining the piezometric surface.
The program will do a total stress analysis.

"CIRCLE (F8.1, F8.1, F8.1) ONLY INTERSECTS SLOPE AT ONE POINT: EXTENT OF GEOMETRY INSUFFICIENT." "STOP EXECUTION OF THIS CIRCLE."

INTER, line 55, format 844.

The specified failure circle only intersects the slope geometry at one point; the line at this point is not tan-

gent to the circle.
The geometry does not cover the extent of the failure circle.
The program will analyse the next failure circle.

"FAILURE CIRCLE (F8.1, F8.1, F8.1) DOES NOT INTERSECT SLOPE."

INTER, line 49, format 94.

The failure circle specified does not intersect any of the segments defining the slope geometry.
The program will analyse the next failure circle.

"LINE (F8.1, F8.1), (F8.1, F8.1) IS ALMOST TANGENT TO FAILURE CIRCLE (F8.1, F8.1, F8.1)."

INTER, line 42, format 64.

The failure circle cuts the slope but the value of the discrement of the circle-line intersection is less than one.

"EFFECTIVE UNIT STRESS VALUE LESS THAN ZERO (F8.1) AND HAS BEEN READJUSTED TO ZERO FOR THE FOLLOWING FAILURE CIRCLE."

FOFS, line 95, format 915.

The effective normal unit stress cannot be less than zero. The calculated value is less than zero and has been readjusted to zero for calculation of the shear strength.

"FAILURE CIRCLE (F8.1, F8.1, F8.1) CUTS SLOPE AT MORE THAN ONE FAILURE SURFACE. PROGRAM WILL ANALYSE EACH SEPARATE PORTION. " FROM F8.1 to F8.1"."

FOFS, line 54, format 405

The specified failure circle defines more than one failure surface with the slope geometry.

Each portion of the failure circle is analysed separately.

"SOIL TYPE 12 UNDER LINE (F8.1, F8.1), (F8.1, F8.1) ON 12 TH CROSS-SECTION CARD CAN'T BE FOUND FOR SLICE CALCULATION. STOP EXECUTION OF THE CIRCLE."

FOFS, line 46, format 35.

The message is a check for malfunctions in the storage procedure of the program. If it occurs the program should be examined for possible misreading of cards.
The program will analyse the next failure circle.

"EFFECTIVE UNIT STRESS VALUE LESS THAN ZERO (F8.1) AND HAS BEEN READJUSTED TO ZERO FOR THE FOLLOWING FAILURE CIRCLE."

FOFS, line , format 915.

The effective normal stress acting on the base of the slice is negative and has been replaced by zero for the rest of the computations.

"PIEZOMETRIC SURFACE DOES NOT EXTEND TO COVER PRESENT PROBLEM. FAILURE CIRCLE (F8.1, F8.1, F8.1) WILL NOT BE EXECUTED."

WEIGHT, line 23, format 46.

Failure circle extension greater than piezometric surface.
Program will analyse next failure circle.
This message will only be printed out if there is a malfunction in the storage procedure of the program. If this occurs, the program should be examined for misreading of card.

Appendix E

TI - 59 PROGRAM LISTING

SIOU TI - 59 PART "A" DATA INPUT

REGISTER ACCOUNTING

0	No slope surface points -1 X 100, no soil interface
1	points -1 X 20, No piez points -1 X1.
2	(N.B.: If last digit = 9, piezometric surface =
3	slope surface).
4	
5	
6	
7	
8	
9	
10	X(even) and Y (odd) coordinates describing the
11	points defining the slope surface
12	(maximum of 7 points allowed)
13	
14	
15	
16	
17	
18	
19	
20	
21	X(even) and Y (odd) coordinates of the points
22	defining the subsoil interface
23	(maximum of 4 points allowed)
24	
25	
26	
27	
28	
29	X(even) and Y(odd) coordinates of the points
30	describing the piezometric surface
31	(maximum of 5 points allowed)
32	
33	
34	
35	

SIOU TI - 59 PART "A" DATA INPUT

36
37
38
39 EQPT LINE "1"
40
41

42
43
44
45 EQPT LINE "2"
46
47

48
49
50
51 EQPT LINE "3"
52
53

54
55
56
57 EPQT LINE "4"
58
59

X(even) and Y(odd) coordinates of the points defining the four equipotential lines (maximum of 3 points allowed per line).

N.B. First point to be input for each line is the intersection with the piezometric surface.

SIOU TI - 59 PART "A" DATA STORAGE

step	program	print out	key in	remarks
			1	Read in side "1" of magnetic card Part "A"
			2	Read in side "2" of magnetic card Part "B"
			A	To initialise the program - Read in slope data
0	2nd Lbl A			
2	CLR			Clear print registers
3	2nd Op 02			Clear Print registers
5	2nd Op 03			Clear print registers
7	2nd Op 04			Clear print registers
9	2nd CMS			Clear data memory
10	1 X ⇄ t			Initialise T-register at 1
12	GTO A'			
14	2nd Lbl			Subroutine c' → to initialise R_2 at -2 (counter for number of pairs of prints).
15	2nd C'			
16	1 +/-			
18	STO 02			
20	CLR			
21	2nd Op 02			
23	2nd Lbl			Subroutine B' → to read in and store X and Y - coordinates
24	2nd B'			
25	2nd Adv			
26	44			
28	2nd Op 01			X-coordinate of point:
30	2nd Op 05	X		for end of file or if
32	R/S		Xi, R/S	no data, press: -B at the end of the "slope"
33	2nd Prt			data
34	STO 2nd Ind 03			-C at
36	2nd Op 23			the end of the "soil"
38	2nd Adv			data

SIOU TI - 59 PART "A" DATA STORAGE

step	program	print out	key in	remarks
39	45			-D at
41	2nd Op 01			the end of the "piez"
43	2nd Op 05	Y		data.
45	R/S		Y_i,	-D' if
46	2nd Prt		R/S	"piez" is equal to
47	STO 2nd Ind 03			"slope"
49	2nd Op 22			-E at
51	2nd Op 23			the end of an equipo-
53	INV SBR			tential line
				-E' at
				the end of all equipo-
				tential lines or if <u>no</u>
				groundwater data.
				Y-coordinate of point
54	2nd Lbl			
55	E			
56	5			
57	SUM 02			
59	42- RCL 03=			
65	2nd X>t 276			
68	48 Rcl 03=			
74	2nd X≥t 285			
77	54 -RCL 03=			
83	2nd X>t 294			
86	GTO 303			
89	2nd Lbl			
90	STO			
91	2nd Adv			
92	2nd Adv			
93	17343337			
101	2nd Op 01			
103	2nd Op 05	EQPT		
105	SBR 2nd C'			
107	SBR 2nd B'			
109	RCL 02			
111	-1=			
114	INV			
115	2nd X=t 107			
118	INV SBR			
119	2nd Lbl			Read in slope surface
				data (maximum 7 points)
120	2nd A'			

SIOU TI - 59 PART "A" DATA STORAGE

step	program	print out	key in	remarks
121	3627323317			
131	2nd Op 01			
133	2nd Op 05	SLOPE		
135	4			
136	STO 03			
138	SBR 2nd C'			
140	SBR 2nd B'			
142	RCL 02			
144	-5=			
147	Inv 2nd X=t 140			
151	2nd Lbl			Read in subsoil interface (maximum 4 points)
152	B			
153	RCL 02			
155	INV			
156	2nd X≥t A			Program will not execute if less than 2 sets of slope surface points
158	X 100=			
163	STO 00			
165	2nd Adv			
166	2nd Adv			
167	36322427			
175	2nd Op 01			
177	2nd Op 05	SOIL		
179	18			
181	STO 03			
183	SBR 2nd C'			
185	SBR 2nd B'			
187	RCL 02			
189	-2=			
192	INV			
193	2nd X=t 185			
196	2nd Lbl C			To read in piezometric surface (maximum 5 points)
198	RCL 02			
200	2nd X≥t 206			
203	0			
204	STO 02			
206	RCL 02			

SIOU TI - 59 PART "A" DATA STORAGE

step	program	print out	key in	remarks
208	X 10=			
212	SUM 00			
214	2nd Adv			
215	2nd Adv			
216	33241746			
224	2nd Op 01			
226	2nd Op 05	PIEZ		
228	26			
230	STO 03			
232	SBR 2nd C'			
234	SBR 2nd B'			
236	RCL 02			
238	-3=			
241	INV			
242	2nd X=t 234			
245	2nd Lbl D			To read in equipotential lines (maximum 4 lines of 3 points each)
247	RCL 02			
249	2nd X≥t 262			
252	0			
253	GTO 262			
256	2nd Lbl			Piezometric surface equal to slope surface
257	end D'			
258	9			
259	SUM 00			
261	2nd E'			
262	SUM 00			
264	36			Equipotential line 1
269	STO 03			
271	2			
272	2nd Op 02	1		
274	SBR STO			
276	42			Equipotential line 2
278	STO 03			
280	3			
281	2nd Op 02	2		
283	SBR STO			
285	48			Equipotential line 3
287	STO 03			
289	4			

SIOU TI - 59 PART "A" DATA STORAGE

step	program	print out	key in	remarks
290	2nd Op 02	3		
292	SBR STO			
294	54			Equipotential line 4
296	STO 03			
298	5			
299	2nd Op 02	4		
301	SBR STO			
303	2nd Lbl			
304	2nd E'			
305	4335243717			
315	2nd Op 01	WRITE		
317	16133713			
325	2nd Op 02	DATA		
327	14260005			
335	2nd Op 03	BK 4		
337	2nd Op 05			
339	4			
340	2nd Write			
341	R/S		R/S	Insert data card side 4 and press R/S
342	14260004			
350	2nd Op 03			
352	2nd Op 05	BK 3		
354	3			
355	2nd Write			
356	R/S			Insert data card side
357	3517131600		R/S	3 and press R/S
367	2nd Op 01	READ		
369	3335220014			
379	2nd Op 02	PRG B		
381	0014260002			
391	2nd Op 03	BK 1		
393	2nd Op 05			
395	1			
396	R/S		R/S	Insert side I of magnatic card part "MB" press R/S
397	0014260003			
407	2nd Op 03			
409	2nd Op 05	BK 2		
411	CLR			
413	2nd Op 02			
414	2nd Op 03			

SIOU TI - 59 PART "A" DATA STORAGE

step	program	print out	key in	remarks
416	2			
417	2nd CP			Zero T-register
418	R/S			Insert side 2 of magnetic card, part "B"
419				Ready to execute part "B"

SIOU TI - 59 PART "B" FCIRC

REGISTER ACCOUNTING

0	Nsl, Nso, Npz	
1		
2		
3		
4		
5		
6		
7		
8		
9		Slope coordinates (registers 3–17)
10		
1		
2		
3		
4		
15		
6		
7		
8		
19		
20		
1		
2		Soil coordinates (registers 18–25)
3		
4		
25		
6		
7		
8		
29		
30		Piezometric coordinates (registers 26–35)
1		
2		
3		
4		
35		
6	Ex_1	
7	Ey_1	
8	Ex_2	
39	Ey_2	X-coordinates of circle EQPT line intersection
40	Ex_3	and corresponding EQPT level. (registers 36–43)
1	Ey_3	
2	Ex_4	
3	Ey_4	

SIOU TI - 59 PART"B" FCIRC

REGISTER ACCOUNTING

4	NEQ → No of EQPT-circle intersection
45	Xb_1
6	
7	
8	
49	
50	
1	
2	
3	
4	
55	CX
6	CY
7	R
8	No of slope points -1
59	BS → Slice width
60	CX
1	CY
2	R
3	$\sqrt{D}$
4	2A
65	-B
6	X_1
7	Y_1
8	X_2
69	m

SIOU TI - 59 PART "B" FCIRC

step	program	print out	key in	remarks
0	2nd Lbl			
1	E			Subroutine to read and store data
2	2nd Op 05			
4	R/S		X_i,Y_i t_i, R/S	Center X, centre Y and radius
5	2nd Prt			
6	STO 2nd Ind 03			
8	2nd Op 23			
10	Inv SBR			
11	2nd Lbl			Subroutine to determine and store intersections of the failure circle and segments
12	D			
13	STO 2nd Ind 02			
15	-RCL 68=			
19	2nd X=t 039			
22	RCL 66			
24	-RCL 2nd Ind 02 ·			
27	)÷(			
30	RCL 68-			
33	RCL 2nd Ind 02=			
36	2nd X≥t 041			
39	2nd Op 22			
41	Inv SBR			
42	2nd Lbl			Subroutine to calculate circle line roots
43	C			
44	RCL 2nd Ind 03			Recall X_1
46	STO 66			
48	2			
49	SUM 03			
51	RCL 2nd Ind 03			
53	STO 68-			
56	RCL 66=			
59	STO 69			$X_2 - X_1$
61	2nd X=t 85			
64	2nd Op 33			
66	RCL 2nd Ind 03			Recall Y_1

SIOU TI - 59 PART "B" FCIRC

step	program	print out	key in	remarks
68	STO 67			
70	2			
71	SUM 03			
73	RCL 2nd Ind 03			Recall Y_2
75	-RCL 67=			
79	÷ RCL 69			
82	= STO 69			Slope of line
85	x 2 x			
88	(RCL 67-			
92	RCL 69 x			
95	RCL 66-			
98	RCL 61)			
101	-2 x			
104	RCL 60			
106	= +/-			
108	STO 65			-B of quadratic equation
110	2x			
112	RCL 69			
114	X^2			
115	+ 2 =			
118	STO 64			2A
120	RCL 65 X^2			
123	- 2 x			
126	RCL 64 x			
129	(RCL 69 x			
133	RCL 66x			
136	(CE			
138	- 2 x			
141	RCL 67			
143	+ 2 x			
146	RCL 61)			
149	+RCL 61 x			
153	(CE -			
156	2 x			
158	RCL 67)			
161	+RCL 60			
164	X^2+			
166	RCL 67 X^2			
169	-RCL 62 X^2			
173	= +/-			D of quadratic equation
175	2nd X≥t 202			
178	+ /-			
179	$\sqrt{X}$			

SIOU TI - 59 PART "B" FCIRC

step	program	print out	key in	remarks
180	STO 63			
182	+RCL 65)			
186	÷RCL 64=			
190	D			
191	RCL 65-			
194	RCL 63)			
197	÷RCL 64=			
201	D			
202	2nd Op 33			
204	Inv SBR			
205	2nd Lbl		A	Press "A" to initiate the program
206	A			
207	7			
208	2nd Op 17			To expand data memory to 70 registers
210	60			
212	STO 03			
214	1544			
218	2nd Op 01	CX		
220	E			
221	1545			
225	2nd Op 01	CY		
227	E			
228	35			
230	2nd Op 01	R		
232	E			
				Calculate the equipotential lines-circle intersections R_1 → counter to store data (intersection)
233	37			
235	STO 01			
237	36			
239	STO 02			R_2 & R_3 → counters to recal coordinates
241	STO 03			
243	C			
244	RCL 67			
246	STO 2nd Ind 01			
248	RCL 02-			
251	Rcl 01=			
254	2nd X≥t 273			

SIOU TI - 59 PART "B" FCIRC

step	program	print out	key in	remarks
257	C			
258	2			
259	SUM 03			
261	RCL 02-			
264	RCL 01=			
267	2nd X≥t 276			
270	GTO 284			
273	4			
274	SUM 03			
276	2nd Op 21			
278	RCL 01			
280	STO 02			
282	2nd Op 21			
284	56-			
287	RCL 03=			
290	2nd X≥t 243			
293	RCL 02			
295	÷2-			
298	18=			
301	STO 44			
303	45			Calculate the equipotential lines circle intersections.
305	STO 02			
307	4			
308	STO 03			
310	C			
311	RCL 02-			
314	47=			
317	2nd X≥t 351			
320	RCL 00			
322	÷100)			
327	2nd Int			
328	STO 58			
330	-RCL 03			
333	÷2			
335	+ 2=			
338	Inv 2nd X=t 310			
342	46-			
345	RCL 02=			
348	2nd X≥t 210			

SIOU TI - 59 PART "B" FCIRC

step	program	print out	key in	remarks
351	RCL 45-			
354	RCL 46)			
357	÷10=			
361	STO 59			
363	RCL 45-			
366	RCL 59			
368	÷2=			
371	STO 45			
373	RCL 60			Place failure circle data in permanent part
375	STO 55			of data memory.
377	RCL 61			
379	STO 56			
381	RCL 62			
383	STO 57			
385	6			Reduce data memory to 60 registers
386	2nd Op 17			
388	1			
389	2nd Prt			
390	R/S		R/S	Read in side 1 of magnetic card part "C" - Press R/S
391	2			
392	2nd Prt			Read in side 2 of magnetic card part "C"
383	R/S			

SIOU TI - 59 Part "C" INTER

REGISTER ACCOUNTING

Register	Contents	Register	Contents
0		40	Circle-Eqpt intersections
1		41	(X) & piezometric ratio.
2		42	
3		43	
4		44	No circle-eqpt inter
5		45	
6		46	
7		47	
8		48	
9	Slice-soil	49	X coordinate of center
10	Y-intersection	50	of base of slice
11		51	
12		52	
13		53	
14		54	
15		55	CX
16		56	CY
17		57	R
18		58	No of slope surface segments
19			
20	Slice-piezometric	59	Slice width
21	Y-intersection	60	
22		61	
23		62	
24		63	
25		64	Slice slope
26		65	Y-intersection
27		66	
28		67	
29		68	
30	Slice-slope	69	
31	Y-intersection	70	
32		71	Counters
33		72	
34		73	
35		74	Free for program
36		75	
37		76	
38		77	
39		78	
		79	

SIOU TI-59 PART "C" INTER

step	program	print out	key in	remarks
0	2nd Lbl			
1	C			
2	0			
3	Sto 2nd Ind 71			
5	2nd Op 21			
7	1			
8	Sum 71			
10	54-			
13	RCL 01=			
16	2nd X≥t 002			
19	Inv SBR			
20	2nd Lbl			Subroutine to calculate slice-geometry intersections.
21	B			
22	RCL 2nd Ind 70-			Xp_2
25	RCL 2nd Ind 01=			$X_2 - X_b$
28	2nd X=t 046			
31	STO 72			
33	RCL 2nd Ind 02-			
36	RCL 2nd Ind 01=			$(X_1 - X_b) / (X_2 - X_b)$
39	÷ RCL 72=			
43	2nd X≥t 091			
46	RCL 2nd Ind 70-			
49	RCL 2nd Ind 02=			
52	STO 72			
54	1			
55	SUM 70			
57	SUM 02			
59	RCL 2nd Ind 70-			
62	RCL 2nd Ind 02=			
65	÷ RCL 72=			Slope of line
69	2nd Op 32			
71	x (			
73	RCL 2nd Ind 01-			
76	RCL 2nd Ind 02=			$m \times (X_b - X_1)$
79	2nd Op 22			
81	+			
82	RCL 2nd Ind 02=			
85	STO 2nd Ind 71			$m \times (X_b + X_1) + Y_1$
87	1			
88	SUM 71			
90	Inv SBR			
91	2			
92	SUM 02			

SIOU TI - 59 PART "C" INTER

step	program	print out	key in	remarks
94	SUM 70			
96	GTO 022			
99	2nd Lbl A		A	Press "A" to initialise program
101	8			
102	2nd Op 17			Expand data memory to 80 registers
104	45			
106	STO 01			X_b counter
108	60			Slice-slope intersection counter
110	STO 71			
112	4			
113	STO 02			
115	6			R_2 & R_{70}, segments co-ordinates
116	STO 70			
118	B			Call subroutine B
119	54-			
122	RCL 01=			
125	2nd X=t 141			Check for last slice
128	RCL 2nd Ind 01			
130	- RCL 59=			X_b
134	2nd Op 21			
136	STO 2nd Ind 01			
138	GTO 112			
141	45			
143	STO 01			
145	6			Counter to store slice-soil intersection
146	STO 71			
148	RCL 00			
150	÷ 10=			
154	2nd Int			
155	- RCL 58			
158	x 10 =			No. of subsoil interface segments
162	STO 73			
164	2nd X=t 190			
167	18			
169	STO 02			
171	20			
173	STO 70			
175	B			

SIOU TI - 59 PART "C" INTER

step	program	print out	key in	remarks
176	2nd Op 21			
178	54-			
181	RCL 01=			
184	2nd X≥t 167			
187	GTO 191			
190	C			
191	45			
193	STO 01			
195	16			
197	STO 71			
199	RCL 00-			
202	RCL 58			
204	x 100-			
209	RCL 73			
211	x 10=			
215	2nd X=t 311			If greater than 4, hydrostatic with piez = slope surface
218	-8=			
221	2nd X≥t 247			
224	26			
226	STO 02			
228	28			
230	STO 70			
232	B			
233	2nd Op 21			
235	54-			
238	RCL 01=			
241	2nd X≥t 224			
244	GTO 269			
247	60			If hydrostatic and slope = piez, transfer same data
249	STO 01			
251	RCL 2nd Ind 01			
253	STO 2nd Ind 71			
255	1			
256	SUM 01			
258	SUM 71			
260	69-			
263	RCL 01=			
266	2nd X≥t 251			
269	36			

STIOU TI - 59 PART "C" INTER

step	program	print out	key in	remarks
271	STO 01			
273	RCL 44			No of circle-equipotential int.
277	2nd X=t 312			No circle-equipotential intersections.
280	4333330002			
290	2nd Op 01			
292	2nd Op 05			
294	1			
295	R/S			
296	GTO 099			
299	---			
310	---			
311	C			
312	1			Ratio =1 for vertical or no equipotentials.
313	STO 44			
315	STO 37			
317	7			Reduce data memory to 70 registers.
318	2nd Op 17			
320	60			Put slice-slope intersections in permanent memory
322	STO 00			
324	26			
326	STO 01			
328	RCL 2nd Ind 00			
330	STO 2nd Ind 01			
332	2nd Op 20			
334	2nd Op 21			
336	35-			
339	RCL 01=			
342	2nd X≥t 328			
345	6			Reduce data memory to 60 registers
346	2nd Op 17			
348	1			Read in side 1 of magnetic card part D, press R/S
349	2nd Prt	1		
350	R/S		R/S	
351	2	2		Read in side 2 of magnetic card part D, press R/S.

SIOU TI - 59 PART "C" INTER

step	program	print out	key in	remarks
352	2nd Prt			
353	R/S			
354	---			Program ready to execute part D.

SIOU TI - 59 PART "C" INTER Subroutine WPP

step	program	print out	key in	remarks
0 to 98				Program steps 0 to 98 inclusively are idenrical to the first part of subprogram INTER
99	5			Subroutine to calcualte equipotential ratio
100	STO 71			
102	26			
104	STO 02			
106	28			
108	STO 70			
110	B			
111	RCL 57			
113	X^2			
114	-((			
117	RCL 55-			
120	RCL 2nd Ind 01			
122	) |X|- -			
125	$\sqrt{X}$ ± +			
128	RCL 56=			
131	STO 04			
133	2nd Op 21			
135	RCL 2nd Ind 01-			
138	RCL 04=			
141	÷(			
143	RCL 05-			
146	RCL 04=			Equipotential ratio: true height / vertical height
149	STO 2nd Ind 01			
151	2nd Op 21			
153	2nd Dsz 3 099			
157	GTO 317			
160	---			

SIOU TI - 59 PART "D" WEIGHT

REGISTER ACCOUNTING

0	
1	
2	1st slices above soil interface
3	1st slices below soil interface
4	
5	
6	
7	
8	
9	
10	$h_{s2} \rightarrow \gamma.ht \rightarrow EUS = \gamma.ht - \gamma w.hw$
1	
2	
3	
4	
15	
6	
7	
8	
19	
20	$hw \rightarrow hw.R.\gamma w \rightarrow tan.X$
21	
2	
3	
4	
25	
6	
7	
8	
29	
30	ht
1	
2	
3	
4	
35	
6	
7	
8	
39	
40	EQPT X coordinate and ratio R
1	
2	
3	

SIOU TI - 59 PART "D" WEIGHT

REGISTER ACCOUNTING

4	
45	
6	
7	
8	
49	X coordinate -- BS ÷ COS of base of slice
50	
1	
2	
3	
4	
55	CX
6	CY
7	R
8	Y coordinate of base of slice
59	BS - Σ W - sinα ÷ BS
60	γw_1
1	γs_1
2	γw_2
3	γs_2
4	Σ W - sinα ÷ BS
65	1st slices above soil interface
6	1st slices below soil interface
7	
8	Free for program
69	

SIOU TI - 59 PART "D" WEIGHT

step	program	print out	key in	remarks
0	2nd Lbl		A	Press "A" to initiate program.
1	A			
2	7			
3	2nd Op 17			Expand data memory to 70 registers.
5	243			
8	2nd Op 01			Enter wet density of soil 1, press R/S.
10	2nd Op 05			
12	R/S			
13	2nd Prt		W_i, R/S	
14	STO 60			
16	236			
19	2nd Op 01			
21	2nd Op 05			Enter saturated density of soil 1, press R/S.
23	R/S		W_i, R/S	
24	2nd Prt			
25	STO 61			
27	343			
30	2nd Op 01			
32	2nd Op 05			Enter wet unit weight of soil 2, press R/S.
34	R/S		W_i, R/S	
35	2nd Prt			
36	STO 62			
38	336			
41	2nd Op 01			
43	2nd Op 05			Enter saturated unit weight of soil 2, press R/S
45	R/S		Wi, R/S	
46	2nd Prt			
47	STO 63			
49	45			Counters to recal X-co-ordinates of base of slice
51	STO 00			
53	26			

SIOU TI - 59 PART "D" WEIGHT

step	program	print out	key in	remarks
55	STO 01			-Slice slope Y-intersection
57	6			
58	STO 02			-Slice-soil Y-intersection
60	16			
62	STO 03			-Slice-piezometric Y-intersection
64	0			
65	STO 64			- to sum W . sinα First encountered slices (base) above and below soil interface
67	STO 65 STO 66			
71	RCL 56-			CY
74	(RCL 57X^2-			R^2
79	(RCL 55-		C	CX
83	RCL 2nd Ind 00			Xb
85	) X^2)			
88	2nd $\|X\|$ $\sqrt{X}$ = +/- 376			Y-coordinate of center of base of slice (negative value)
92	STO 58 +			
95	RCL 2nd Ind 02=			Y-coordinate slice-soil
98	2nd X≥t 114			Count first slices above R65 and below R66 soil interface for shear properties
101	2nd IF Fig 01 108			
105	1 SUM 65			
108	0 STO 2nd Ind 02			
111	GTO 121			
114	STO 2nd Ind 02			
116	2nd Stfig 01			
118	1 SUM 66			
121	RCL 58+			Y-coordinate of base of slice → YB
124	RCL 2nd Ind 01=			Y-coordinate of slice slope intersection
127	STO 2nd Ind 01			Height of slice below slope surface → ht

<u>SIOU TI - 59 PART "D" WEIGHT</u>

step	program	print out	key in	remarks
129	RCL 58+			Y-coordinate slice-piezometric - YB
132	RCL 2nd Ind 03=			Height of slice below the piezometric surface → hw
135	2nd X≥t 139			
138	0			
139	STO 2nd Ind 03			Computation of total stress:
141	-RCL 2nd Ind 02=			Height of slice to piezometric surface.
145	2nd X≥t 180			Height of slice to soil interface
148	RCL 2nd Ind 01-			a) piezometric surface below subsoil interface
151	RCL 2nd Ind 02=			
154	x RCL 60+			ht - hs_2
158	(RCL 2nd Ind 02-			
162	RCL 2nd Ind 03)			
165	x RCL 62+			
169	RCL 03 x			
172	RCL 63=			
175	STO 2nd Ind 02			γ.ht -- total unit stress
177	GTO 229			
180	RCL 2nd Ind 01-			
183	RCL 2nd Ind 03=			b) piezometric surface above subsoil interface
186	2nd X≥t 206			
189	2nd |X| x			
191	62.4 +			
196	(RCL 2nd Ind 01-			
200	RCL 2nd Ind 02)			
203	GTO 217			
206	x RCL 60+			
210	(RCL 2nd Ind 03-			
214	RCL 2nd Ind 02)			
217	x RCL 61+			
221	RCL 2nd Ind 02			
223	x RCL 63=			
227	STO 2nd Ind 02			

SIOU TI - 59 PART "D" WEIGHT

step	program	print out	key in	remarks
229	36			
231	STO 04			
233	RCL 44			
235	-1=			
238	STO 05			To determine if slice is between surface and 1st intersection
240	2nd X=t 270			
243	RCL 2nd Ind 04-			
246	RCL 2nd Ind 00=			
249	2nd X≥t 270			
252	STO 58			
254	2			
255	SUM 04			
257	RCL 2nd Ind 04-			
260	Rcl 2nd Ind 00=			
263	2nd X≥t 277			
266	2nd Osz 5 252			
270	2nd Op 24			
272	RCL 2nd Ind 04			
274	GTO 291			
277	SUM 58			
279	RCL 58			
281	2nd X≥t 270			
284	2 +/- SUM 04			
288	GTO 270			
291	x RCL 2nd Ind 03x			
295	62.4=			hw x R÷γw(effective g.w. height/true c.w. height) note to use unit porewater pressure
300	STO 2nd Ind 03			
302	RCL 55-RCL 2nd Ind 00=			
308	÷RCL 57=			Sinα . to analyse slope facing the origin (reverse), sinα = -sinα x (+/-)
312	STO 58			
314	x RCL 2nd Ind 02=			
318	SUM 64			Σ W.sinα ÷ BS
320	RCL 58			
322	Inv 2nd Sin			

SIOU TI - 59 PART "D" WEIGHT

step	program	print out	key in	remarks
324	STO 58			α
326	2nd Cos			
327	STO 05			
329	RCL 2nd Ind 02-			
332	RCL 2nd Ind 03=			γ.h - γw.hw
335	2nd X≥t 339			
338	0			
339	STO 2nd Ind 02			
341	RCL 58			
343	2nd Tan 2nd |X|			
345	STO 2nd Ind 03			Tanα
347	Rcl 59 ÷			BS ÷
350	RCL 05= 2nd |X|			Cosα
354	STO 2nd Ind 00			λ= BS÷ cosα
356	2nd Op 20			
358	2nd Op 21			
360	2nd Op 22			
362	2nd Op 23			
364	54- RCL 00=			
370	2nd X≥t 071			
373	RCL 64 x			
376	RCL 59 2nd|X|=			Σ W.sinα
380	STO 59			
382	RCL 65			
384	STO 02			
386	RCL 66			
388	STO 03			
390	6 2nd Op 17			
393	Inv			
394	2nd Stfig 01			Reduce data memory to 60 registers
396	1	1		Read in side 1 of magnetic card part "E", press R/S
397	2nd Prt			
398	R/S		R/S	
399	2	2		Read in side 2 of magnetic card, part "E"
400	2nd Prt			
401	R/S			Program part "D" ready to execute.

SIOU TI - 59 PART "E" FOFS

REGISTER ACCOUNTING

Register	Contents	
0		
1		
2		
3		
4		
5		
6	Effective unit shear strength - τ	
7	Effective unit shear strength - τ	
8	Effective unit shear strength - τ	
9	Effective unit shear strength - τ	
10	Effective unit shear strength - τ	
1	Effective unit shear strength - τ	
2	Effective unit shear strength - τ	
3	Effective unit shear strength - τ	
4	Effective unit shear strength - τ	
15	Effective unit shear strength - τ	
6		
7		
8		
9		
20		
1		
2		
3		
4		
25		
6	c'	Soil 1
7	$\sigma n'1$	Soil 1
8	$\tau'1$	Soil 1
9	$\sigma n'2$	Soil 1
30	$\tau'2$	Soil 1
1	$\sigma n'3$	Soil 1
2	$\tau'3$	Soil 1
3	c'	Soil 2
4	$\sigma n'1$	Soil 2
35	$\tau'1$	Soil 2
6	$\sigma n'2$	Soil 2
7	$\tau'2$	Soil 2
8	$\sigma n'3$	Soil 2
39	$\tau'3$	Soil 2

REGISTER ACCOUNTING

40	
1	τi
2	
3	
4	F of S Assumed
45	
6	
7	
8	
9	
50	
1	
2	
3	
4	
55	
6	
7	
8	F of S Calculated
9	
60	
1	
2	
3	
4	
65	Slope of Mohr-Coulomb Envelope $\tan \phi'$ (registers 60–69)
6	
7	
8	
69	

SIOU TI - 59 PART "E" FOFS

step	program	print out	key in	remarks
0	2nd Lbl B			
2	2nd Op 05			
4	R/S		R/S	Key in shear parameters punch R/S
5	2nd Prt			
6	STO 2nd Ind 00			
8	2nd Op 20			
10	Inv SBR			
11	2nd Lbl A			Press "A" to initiate program. Read in shear parameters
13	26			
15	STO 00			
17	2			
18	STO 01			
20	2			
21	2nd Op 02			
23	363227			
29	2nd Op 01			
31	2nd Op 05	SOL 1		
33	0			
34	2nd Op 02			
36	15	C		Cohesion or τ' - intercept
38	2nd Op 01			
40	B			
41	236	SI		σn' coordinate of first point
44	2nd Op 01			
46	B			
47	237	T1		τ' coordinate of first point
50	2nd Op 01			
52	B			
53	336	S2		σn' coordinate of second point
56	2nd Op 01			
58	B			
59	337	T2		τ' coordinate of second point
62	2nd Op 01			
64	B			

SIOU TI - 59 PART "E" FOFS

step	program	print out	key in	remarks
65	436	S3		σn' coordinate of third point
68	2nd Op 01			
70	B			
71	437	T3		τ' coordinate of third point
74	2nd Op 01			
76	B			
77	3			
78	2nd Op 02			
80	2nd Dsz 1 23			
84	0			
85	2nd Op 02			
87	7			
88	2nd Op 17			Expand data memory to 70 registers counters: - to recall the effective unit stress and store τ' - to store tanϕ' - for the number of slices
90	6			
91	STO 00			
93	60			
95	STO 05			
97	10			
99	STO 01			
101	RCL 02			Routine to determine soil type at base of slice
103	2nd X=t 113			
106	27			
108	STO 04			
110	GTO 117			
113	34			
115	STO 04			
				Routine to calculate slice stress range
117	RCL 2nd Ind 00			
119	2nd X=t 276			if exit, τ'=c', tanϕ=0
122	Rcl 2nd Ind 04-			σnl'

SIOU TI - 59 PART "E" FOFS

step	program	print out	key in	remarks
125	RCL 2nd Ind 00=			EUS
128	2nd X≥t 244			If exit, shear strength from 1st segment of envelope
131	2			
132	SUM 04			
134	RCL 2nd Ind 04			$\sigma n_2'$
136	2nd X=t 240			If exit, single straigth line failure envelope
139	-			
140	RCL 2nd Ind 00=			
143	2nd X≥t 179			
146	2			
147	SUM 04			
149	RCL 04			Check if previous points if last or next 0
151	-33=			
155	2nd X=t 175			
158	RCL 04			
160	-40=			
164	2nd X=t 175			
167	RCL 2nd Ind 04			
169	2nd X=t 175			
172	GTO 139			
				a) Stress range between $\sigma n'_1$ and $\sigma n'_3$
175	2 +/-			
177	SUM 04			Determine tanΦ'
179	RCL 2nd Ind 04			$\sigma n' \rightarrow X_2$
181	STO 40			
183	2 +/-			
185	SUM 04			
187	RCL 2nd Ind 04			$\sigma n' \rightarrow X_1$
189	-			
190	RCL 40=			$X_2 - X_1$
193	STO 40			
195	2nd Op 24			
197	RCL 2nd Ind 04			$\tau' \rightarrow Y_1$
199	STO 41			
201	2			
202	SUM 04			
204	RCL 2nd Ind 04-			$\tau' \rightarrow Y_2$

SIOU TI - 59 PART "E" FOFS

step	program	print out	key in	remarks
207	RCL 41=			$y_2 - y1$
210	÷			
211	RCL 40=			$m = \frac{Y_2-Y_1}{X_2-X_1} = \tan\phi'$
214	STO 2nd Ind 05			
216	RCL 2nd Ind 04			$\tau' \rightarrow Y_2$
218	STO 41			
220	2nd Op 34			Determine τ'
222	RCL 2nd Ind 00-			$\sigma n'$ $y=y_1 + m(X-X_1)$
225	RCL 2nd Ind 04=			EUS $\tau'=\tau_i-\tan\phi$ $(\sigma n' - \sigma n_i')$
228	x RCL 2nd Ind 05			$\tan\phi'$
231	+ RCL 41=			$\tau' \rightarrow$ Y_2 or c'
235	STO 2nd Ind 00			Effective unit shear strength
237	GTO 285			
240	2 +/-			b) stress range below σn_i. Determine $\tan\phi'$
242	SUM 04			
244	RCL 2nd Ind 04			$\sigma n_i{}^1 \rightarrow X_2$
246	STO 40			
248	2nd Op 24			
250	RCL 2nd Ind 04			
252	STO 41			τ_1' Y_2
254	2 +/-			
256	SUM 04			
258	RCL 2nd Ind 04-			$c' \rightarrow Y_1$
261	RCL 41=			
264	÷ RCL 40= |X|			
269	STO 2nd Ind 05			
271	2nd Op 24			
273	GTO 222			Determine τ'
276	2nd Op 34			c) EUS = 0
278	RCL 2nd Ind 04			
280	STO 2nd Ind 00			$\tau'=c'$
282	0			
283	STO 2nd Ind 05			$\tan\phi'=0$
285	2nd Op 31			
287	RCL 01			
289	2nd X=t 307			

SIOU TI - 59 PART "E" FOFS

step	program	print out	key in	remarks
292	2nd Op 25			
294	2nd Op 20			
296	2nd Dsz 2 106			
300	2nd Dsz 3 113			
304	GTO 106			
307	2			
308	STO 44			initial factor of saf-ety
310	0			
311	STO 42			To sum each slice
313	6			
314	STO 00			EUS
316	16			
318	STO 01			tan α
320	45			
322	STO 02			λ=BS÷ cosα
324	60			
326	STO 03			tanϕ'
328	RCL 2nd Ind 00 x	EUS		
331	RCL 2nd Ind 02 ÷			BS÷ cosα=λ
334	(RCL 2nd Ind 01 x			tanα
338	RCL 2nd Ind 03			tanϕ
341	RCL 44			F of S
343	+1)=			
347	SUM 42			
349	2nd Op 20			
351	2nd Op 21			
353	2nd Op 22			
355	2nd Op 23			
357	15-			
360	RCL 00=			
363	2nd X≥t 328			
366	RCL 42 ÷			
369	RCL 59=			
372	STO 58			
374	-RCL 44=			
378	2nd |X|-.01=			Iteration central
384	Inv 2nd X≥t 395			
388	RCL 58			
390	STO 44			
392	GTO 310			
395	RCL 58			
397	2nd Prt			
398	R/S			

Appendix F

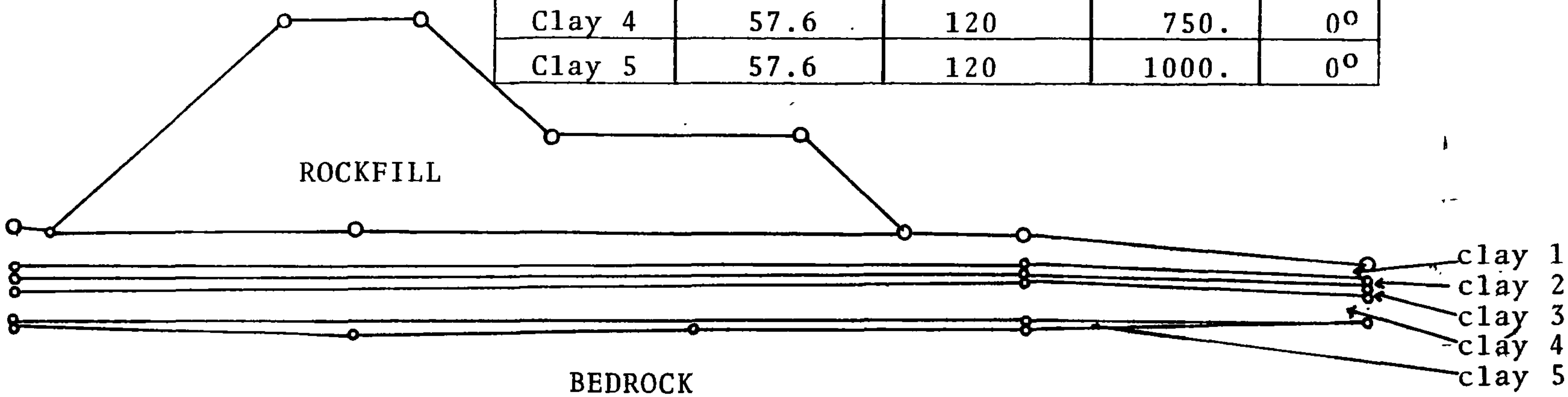
EXAMPLE RUNS

Factor of Safety

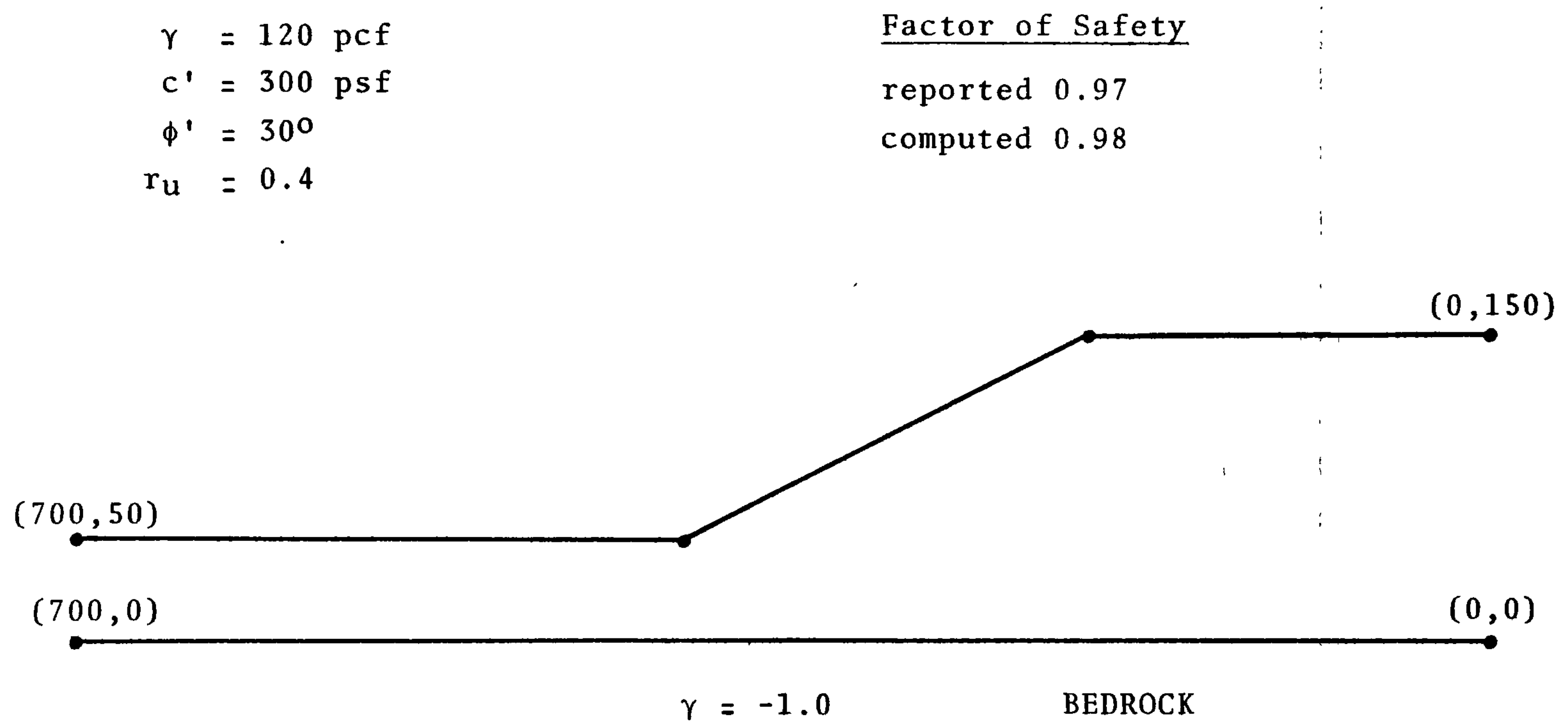
reported 2.11

computed 2.03

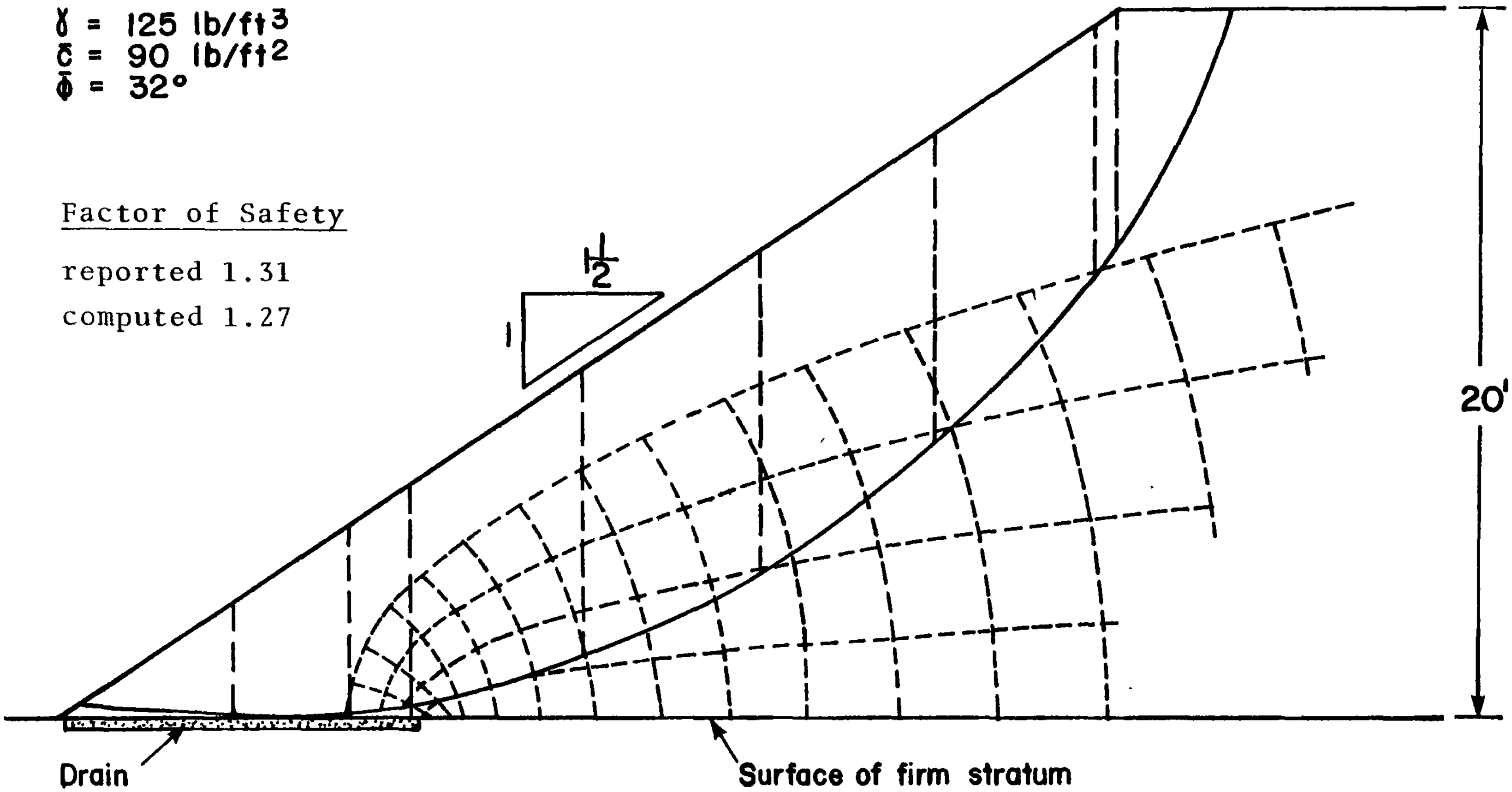
MATERIAL	DENSITY (PCF)		c'(psf)	ϕ'
	submerged	above W.L.		
Rock	77.6	140	0.	42°
Clay 1	57.6	120	3000.	0°
Clay 2	57.6	120	2000.	0°
Clay 3	57.6	120	1300.	0°
Clay 4	57.6	120	750.	0°
Clay 5	57.6	120	1000.	0°



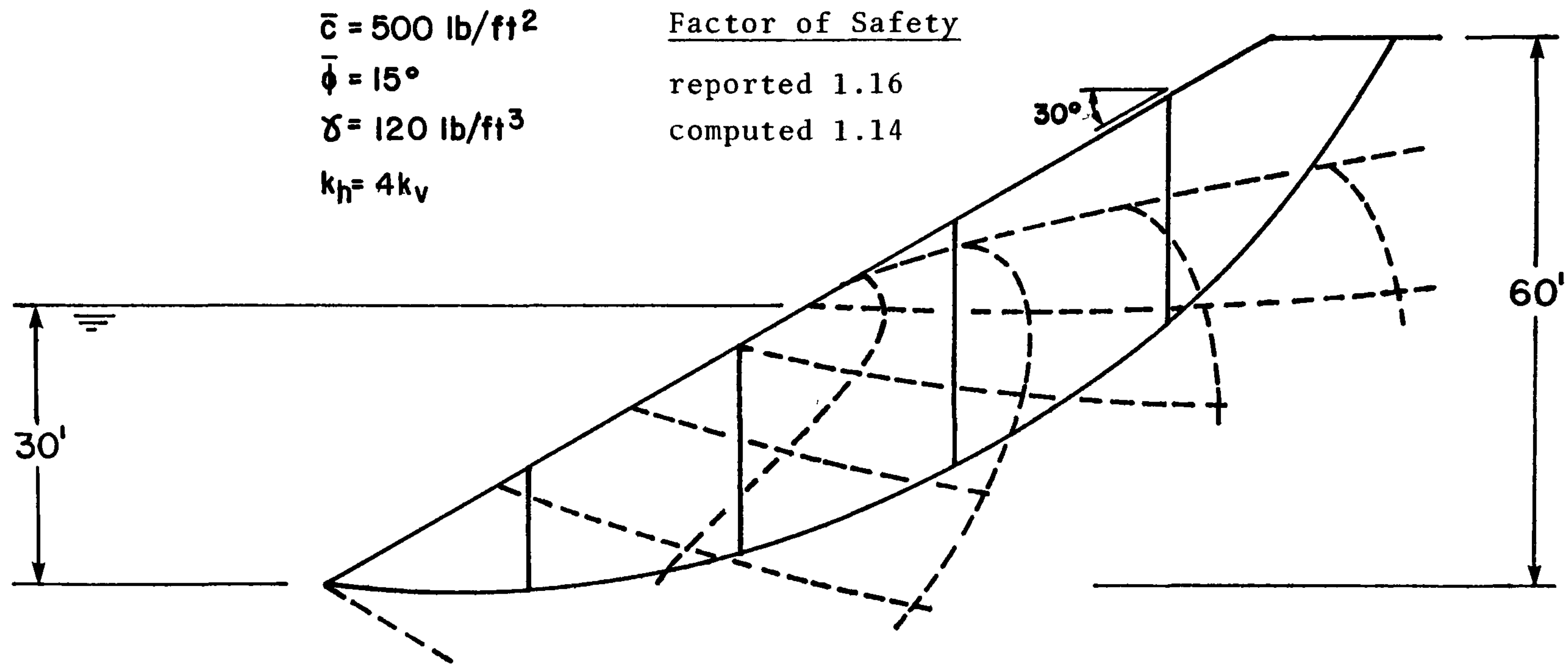
Example 1 SOIL PROPERTIES (from St-Louis, 1978)



Example 2 SIMPLIFIED BISHOP METHOD (from Fredlund, 1977)

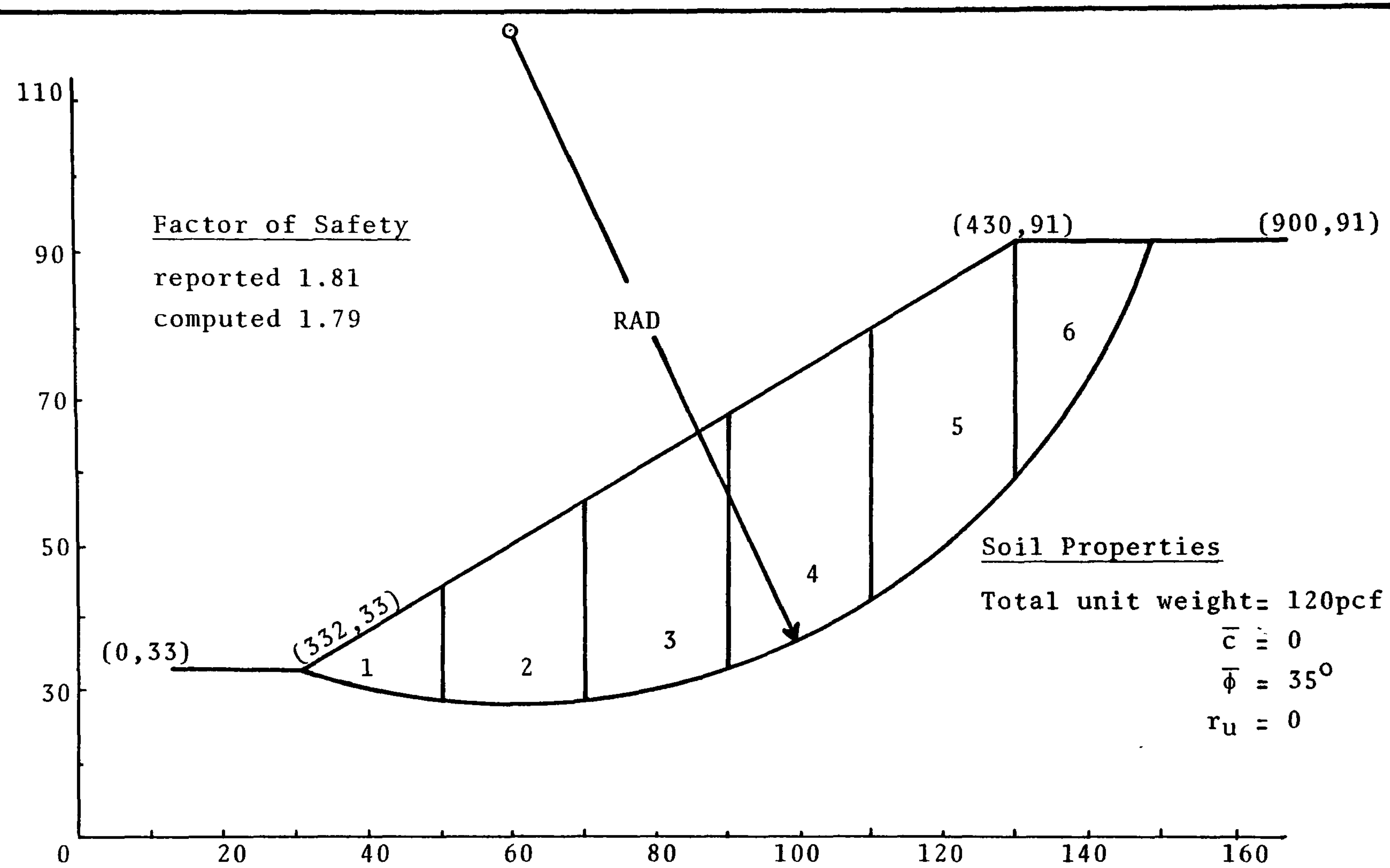


Example 3 **STEADY SEEPAGE** (from Whitman and Moore, 1963)

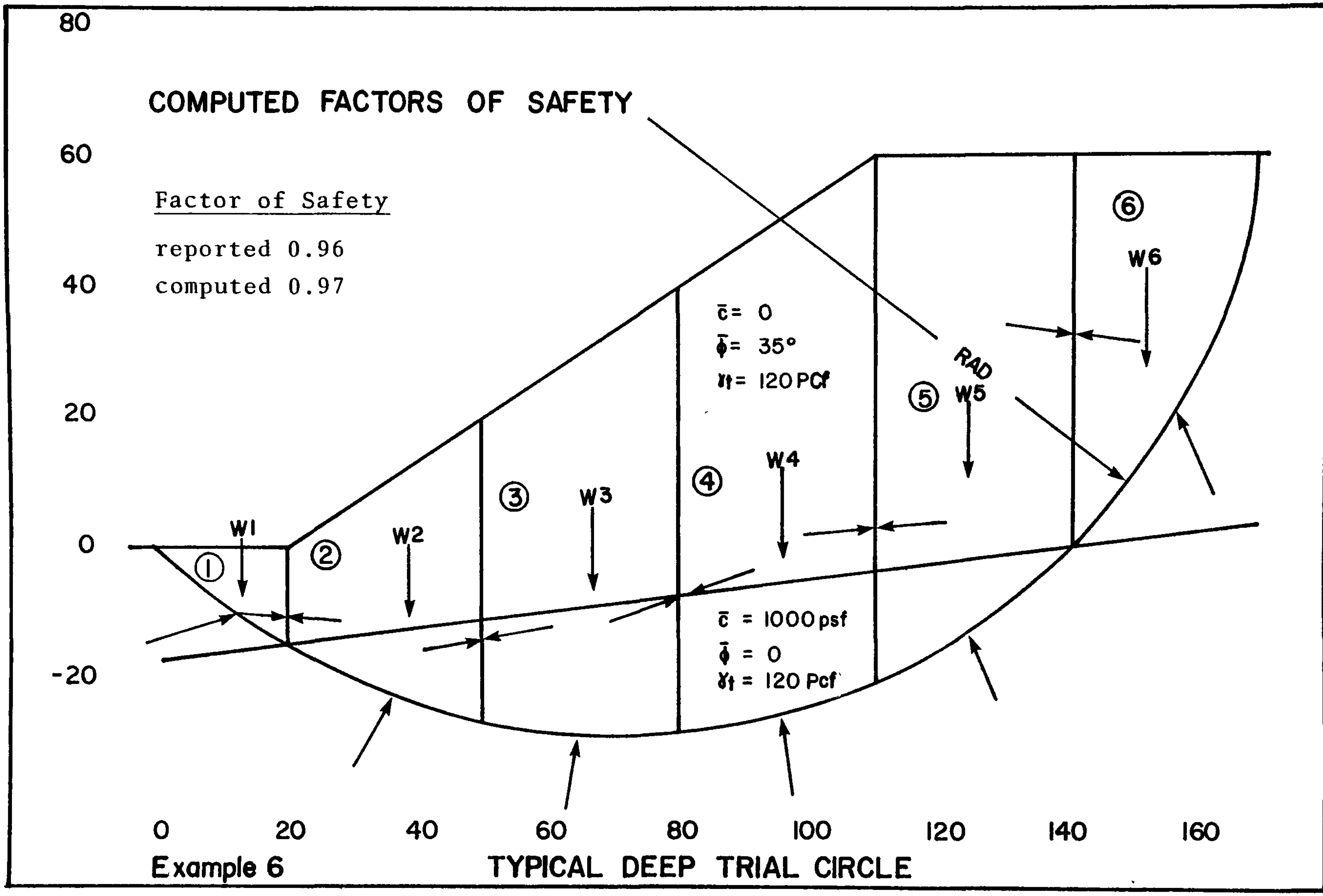


Example 4 — SEEPAGE FOLLOWING DRAWDOWN

(from Whitman and Moore, 1963)



Example 5 TYPICAL TRIAL FAILURE SURFACE THROUGH HOMOGENEOUS, COHESIONLESS SOIL (from Bailey and Christian, 1969)


COMPUTED FACTORS OF SAFETY
Factor of Safety
reported 0.96
computed 0.97
c̄ = 0
φ̄ = 35°
γt = 120 PCf
c̄ = 1000 psf
φ̄ = 0
γt = 120 Pcf
W1
W2
W3
W4
W5
W6
RAD
1
2
3
4
5
6
80
60
40
20
0
-20
0
20
40
60
80
100
120
140
160
Example 6
TYPICAL DEEP TRIAL CIRCLE

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