OPTIMIZATION OF OPEN PIT ANGLES
FROM THE PROBABILITY OF FAILURE

by

RICHARD D. CALL[1]
JACK A. CALDWELL[2]
NED B. LARSON[3]

CIM
4TH OPEN PIT OPERATORS CONFERENCE
SEPTEMBER 27-29
EDMONTON ALBERTA

1 PRESIDENT, CALL & NICOLAS, TUCSON

2 MANAGER, STEFFEN ROBERTSON AND KIRSTEN, VANCOUVER

3 ENGINEER, CALL & NICOLAS, TUCSON

INTRODUCTION

This paper describes methods used to evaluate the stability of various slope geometries for surface strip mines, cut into sequences of essentially horizontal layers of sands, silts and clays. The methods are illustrated by reference to a project in central Texas.

Fig. 1 shows a cross section of the type of stratigraphy and slope, the stability of which may be evaluated by the methods described. The strip mine will be developed to exploit one or more horizontal or near horizontal coal or lignite seams. Between the seams to be mined are a number of horizontal or near horizontal sequences of sands, silts or clays or mixtures of all three. Stratigraphic information across the site is obtained primarily from boreholes which have been geophysically logged. At only a few boreholes have soil or rock samples been obtained.

In order to evaluate slope geometry the probability of failure of slopes of different angles is required. The probability of failure is calculated at any desired geophysically logged borehole from data on the variability of the strength of the different geophysically coded stratigraphic units.

Because of inherent variability of the location of stratigraphic units in a slope, their properties, and uncertainties in sampling and testing, it is not possible to obtain unique values for the geometry and strength of the slope. Presenting results of stability analyses in the form of probability of instability makes it possible to compare stripping costs to instability costs; hence an economic optimum can be determined.

DEFINITION OF MINE GEOLOGY CODED UNITS

General

The geology of the site described in the example in this paper is a series of gently dipping beds of mudstones, sandstones, lignite, carbonaceous clays and silty clays. The method of analysis described is applicable to a pit or to slopes cut into horizontal or near horizontal stratigraphic sequences of varying lithology. Indeed the analytical procedures may be used even if the distribution of soil types in the slope is complex; more effort will be needed, however, to compile data and do the computer analyses.

As part of the exploration of the lignite or coal deposit and the definition of its distribution, a large number of boreholes are drilled and geophysically logged. One or more of the numerous geophysical methods may be used. For example, gamma ray, density, caliper and resistivity probes were used in the example described later.

Geologists interpret the geophysical logs, primarily to identify the coal and lignite seams. They usually describe the material between seams by "coding" it as a sand, silt or clay. Definition of lithology by geophysical methods is subject to the limitations and sensitivities of the method itself as well as human interpretations of data. Consequently a geophysically coded unit such as a sand may actually be a sandy silt, or a varying sequence of layers of sand, silty sand and slightly clayey sand.

Thus in a deposit consisting of a number of lignite or coal seams each might be designated A, B, C, etc. with increasing depth. The soil sequence in between the lignite sequences would accordingly be called, for example, an AB sand: this would indicate a predominantly sandy layer between the A and B lignite seams; a CD silt would indicate a predominantly silty layer between the C and D lignite seams.

An important point to note; a geophysically coded unit does not necessarily consist of the lithology implied by its coded name. A coded sand, for instance, might actually vary from a clean sand to, in extreme cases, a clay. Even though geophysical coding is not without inaccuracies and uncertainties, the coding tends to be consistent. Because the coding is consistent, a general model of the true lithologic make up of the geophysically coded units may be constructed.

Coded Unit Modelling

In order to model the lithology of a coded unit, new boreholes are required from which continuous core is obtained. The holes from which the cores are obtained are geophysically logged and coded, preferably by those who coded the exploration holes and without reference to the cores or geotechnical logs of the core. The complete length of core from each unit is examined in the laboratory. The core is described according to standard geotechnical methods: its actual lithology is described. Such an examination might, for example, reveal that the 30 m length of the unit coded as, say, a sand, consisted of 20 m of sand and 10 m of sandy silt.

Table 1 lists the nine lithologic categories defined for use in modelling coded unit lithology. Thus the actual soil type of the core is taken to fall into at least one of the categories which range from a pure sand through clay sand, and silt clay to clay.

Once the core from all boreholes drilled as part of the geotechnical investigation has been examined and logged and the actual lithologic make up of each coded unit has been tabulated, the following is done for each coded unit defined: the lithologic information for the given coded unit from all the geotechnical boreholes is pooled and tabulated.

The procedure is repeated for each coded unit. The resulting model is a percentage description, in terms of actual lithology, for each coded unit. For example, a coded B.C. clay may be, on the basis of the B.C. clay examined in 10 boreholes, 5 per cent sandy silt, 30 per cent clayey

TABLE 1

LITHOLOGIC UNITS

SOIL	CODE
Sand	SD
Silty Sand	
Clayey Sand	
Silt	SL
Sandy Silt	
Clayey Silt	
Clay	CL
Sandy Clay	
Silty Clay	

silts, 7 per cent clay and 58 per cent clay.

DETERMINATION OF MATERIAL PROPERTIES

For each lithologic unit samples are tested in the laboratory to determine: soil classification, moisture content, gradation, Atterberg Limits, specific gravity, consolidation characteristics and strength distribution. All but the last are standard tests and are not described further here.

The distribution of strength was obtained by direct shear box testing of the soils. Direct shear was chosen in preference to triaxial testing as it more nearly represents the failure mechanism, or at least the mathematical model used to analyze the slope stability. Lamb and Whitman (1969) note:

> "There are certain field situations which present loadings that cannot be duplicated in the triaxial machine. For example, a long embankment imposes plane strain in the underlying soil. A plane strain device is thus needed to simulate this field condition."

Samples tested are sheared parallel to bedding; this may yield conservative results, but testing perpendicular to bedding would yield unrealistically high strengths because the presence of slickensides and vertical jointing in the mass is not accounted for in the shear box. Samples were sheared slowly so that excess pore pressures were not generated. Both peak and residual strengths were measured. Peak strengths are used to evaluate short term stability such as high-wall areas. Residual strengths are used to evaluate long term stability such as in the flankwalls.

Fig. 2 shows a series of four shear tests on a particular lithologic unit. The peak strength is attained at the point of maximum shear load.

The residual shear strength is attained when an increase in the shear displacement is not accompanied by an increase in the shear load. Normal stress versus shear stress are plotted, the relationships statistically analysed, and the shear strength parameters determined. The method is described in detail by Call (1981).

Fig. 3 shows the results for a sand unit. The linear fit is:

$\tau = c + \sigma \mu$ where τ = shear strength
c = cohesion
σ = normal stress
μ = coefficient of friction

Concave curves on either side of the mean line indicate the standard deviation of the mean shear strength. For simplicity of calculation, these curves are approximated by straight lines in the range of normal stresses applied during testing. The difference in intercept between one of these lines and the mean fit is the cohesion standard deviation parameter. The difference in slopes is the coefficient of friction standard deviation parameter.

A sufficient number of samples were tested to obtain the distribution of shear strength of each soil type or lithology. Thus the variability of shear strength of a true sand was measured. Similarly and independently, the variability of the shear strength of a true silty sand is measured.

DETERMINATION OF THE PROBABILITY OF FAILURE

General

Determination of the probability of instability depends on quantifying the variable character of geologic parameters. Since geologic parameters such as shear strength do not have unique values but consist of a distribution of friction angles and cohesions with a dispersion representing the variability of the material and uncertainty of testing, statistical distributions are used to represent them. Where stratigraphy has been defined by geophysical methods, statistical distributions of actual lithologies and strength parameters for a geophysically coded unit also incorporate uncertainties associated with geophysical methods.

The probability of instability is determined using a technique called Monte Carlo simulation. The Monte Carlo method is used to obtain a distribution of safety factors; this involves an iterative process of randomly sampling strength values from a sampled shear strength distribution and then calculating the safety factor.

Shear Strength

From the reduction of the shear strength data, a mean cohesion (c) and a mean coefficient of friction (μ) are calculated. Parameters describing the variability of cohesion and coefficient of friction are calculated as described by Call (1981). These parameters are not the standard deviation of c and μ; they are artificially calculated terms which define the variability of shear strength (τ), given a normal stress (σn).

The exact process is:

- a random number is generated from the standard normal distribution, N(0,1), and displacements from the mean are calculated for both the c and μ distributions. This statistical sampling of the strength distributions to obtain "new" material properties is done with the formula

$$x = \bar{x} + (R) \cdot (Sx)$$

where

x = the value of variable x
$\bar{x}$ = the mean value of variable x
R = standard normal - random number
S_x = standard deviation parameter of x.

The process is repeated for the strength distributions of each lithologic unit. The resulting c's and μ's are used in stability analyses to calculate a safety factor.

An important concept to remember is that one random number is used to define both the Monte Carlo c and μ. Thus one random number generates one shear strength. The c and μ parameters are simply numeric values used to represent the shear strength.

STABILITY ANALYSES

The modified Bishop's analysis is used to analyze the rotational shear failure mode. In order to do a probablistic analysis, a Monte Carlo sampling overlay was incorporated into a computerised Bishop's modified method adapted from the program STABR. The addition of the sampling overlay gives a method of analysis which incorporates the shear strength and the unit weight dispersion characteristic of the natural materials; also included are the uncertainties associated with the geophysical definition of the material.

The Bishop method involves dividing the failure zone into a number of vertical slices. The stability of each slice is determined, hence the stability of the overall potential failure mass is calculated. In order to determine the stability of a slice, the shear strength along the base of the slice is required. The base of the slice will occur in a given coded unit. A two stage Monte Carlo sampling routine is used to obtain a strength along the base of the slice in the given coded unit.

The first stage consists of Monte Carlo selection of an actual lithology from the modelled distribution of actual lithologies for a particular geophysically coded unit. Once the lithology has been selected, the second stage consists of Monte Carlo selection of a shear strength for that lithology selected in the first stage.

The procedure used to calculate the probability of failure is as follows: The most frequently occurring lithology for each coded unit in the slope section being analyzed is selected as representative of the coded unit encountered. For the mean values of the material properties for each lithology, the failure arc with the lowest factor of safety is found. The completion of this step is comparable to a conventional deterministic stability analysis.

Next an actual lithology is randomly selected in a statistical fashion from the distribution of possible lithologies for each geophysically coded unit in the slope section. Shear strength for each lithology selected, is then randomly selected in a statistical fashion from the strength distribution for that particular lithology.

The failure arc determined in the deterministic analysis is used as a starting point of a search to locate the arc of the failure surface with the minimum factor of safety for the "new" material properties. This procedure is repeated 50 to 100 times.

If a normal distribution of safety factors is assumed, the calculated mean and standard deviation of 50 to 100 analyses may be used to calculate the probability of failure. The percentage of the total area of the factor of safety distribution curve is the probability of failure of the slope.

APPLICATION OF THE METHOD

The approach to the evaluation of the probability of failure described above was used to study the slopes to be cut at a strip mine in central Texas: the Phillips Coal Company's Cole Creek lignite surface mine, located as shown in fig. 4. Encountered in the mine area are formations of the Wilcox and Clairbourne Groups and Holocene and Pleistocene terrace deposits. See fig. 5 for the stratigraphic column.

The Calvert Bluff formation of the Wilcox Group contains lignite beds. The formation consists mostly of mudstones with varying amounts of sandstone, lignite and ironstone. Carrizo sands overlie the Calvert Bluff, and consist mostly of quartz sands and mudstones.

The geologic data base consisted of 1700 coded geophysical logs of exploration and development holes. The material types interpreted from the geophysical log included sand, silt, clay, lignite, carbonaceous material and hardstreaks. In addition, the stratigraphic location of the interpreted lithology is identified relative to the lignite seam present. Thus a unit coded CLBC is a clay between B and C lignite seams. A total of 79 units of the stratigraphic sequence were identified.

In order to obtain samples to test, and to define the lithology of coded units, eight continuous coreholes were drilled with two Failing rigs. Core was obtained with a Pitcher Sampler or a 3 m Christiansen core barrel. Core was logged on site and numerous 150 mm samples taken for testing. Holes were geophysically logged using calipers, gamma ray, density and resistivity probes. A typical borehole log is shown in fig 6. Table 2 gives the lithology of the coded units encountered.

Many shear box samples were tested and the results analyzed as described above. Tables 3(a) and (b) summarize the results. These are the material properties used in the stability analyses.

Since the preliminary mine plan for the Cole Creek Project was based on a highwall design angle of 55^{o}, this was chosen as the base case. All analyses were run for zero pore pressure as the mine plan calls for slope dewatering, where rapid natural drawdown does not occur.

Analyses for numerous mining situations were done. As an example the analysis for dragline mining of the B seam lignite involved determining the probability of failure at sixteen of the geophysically coded holes. Only three of the sixteen holes analyzed had probabilities of instability greater than 10 percent. Breakback distances ranged from 6m to 15m. Failure volumes ranged from 120 to 330 m^3/m of highwall. Holes with higher probabilities of instability tended to be in areas of thicker overburden.

Holes with a high probability of instability were re-analyzed at other angles in order to determine the sensitivity of stability to slope angle and to provide the necessary data for economic risk analysis. In most cases flattening the slope angle caused the probability of instability to drop off significantly at angles well above the minimum no-rehandle angle for the slope height analyzed. As slope angles decreased, failure volumes and breakback distances decreased. Results generated as part of this study formed the basis of ongoing studies.

Table 2

PERCENT COMPOSITION OF EACH CODED UNIT ENCOUNTERED DURING FIELD INVESTIGATION

	Wilcox Sand	Wilcox Silty Sand	Wilcox Clayey Sand	Wilcox Silt	Wilcox Sandy Silt	Wilcox Clayey Silt	Wilcox Clay	Wilcox Sandy Clay	Wilcox Clayey Clay	Carrizo Sand
SDDE	3.4	82.5	0.0	6.8	1.7	3.4	0.0	0.0	2.3	0.0
SLDE	0.0	20.5	0.0	25.8	12.1	41.7	0.0	0.0	0.0	0.0
CLDE	0.0	11.5	0.0	0.0	0.0	19.2	17.3	0.0	51.9	0.0
SDCD	28.9	62.6	0.0	6.6	1.9	0.0	0.0	0.0	0.0	0.0
SLCD	0.0	35.6	0.0	11.9	11.9	0.0	35.6	0.0	5.1	0.0
CLCD	0.0	0.0	0.0	0.0	0.0	0.0	74.1	0.0	25.9	0.0
SDBC	27.7	56.4	0.0	0.0	0.0	11.9	0.0	0.0	4.0	0.0
SLBC	0.0	14.0	0.0	3.6	39.6	41.4	0.0	0.0	1.4	0.0
CLBC	0.0	0.0	0.0	0.0	4.6	30.6	6.5	0.0	58.3	0.0
SDAB	6.3	67.6	0.0	3.6	9.0	9.9	1.8	0.0	1.8	0.0
SLAB	0.0	28.6	0.0	22.9	24.0	20.0	0.0	0.0	4.6	0.0
CLAB	0.0	14.5	0.0	0.0	4.8	38.7	33.9	0.0	8.1	0.0
SDE+	44.0	6.0	0.0	22.0	4.0	0.0	0.0	0.0	24.0	0.0
SLE+	0.6	11.2	0.0	7.7	34.3	25.4	13.6	0.0	7.1	0.0
CLE+	37.5	0.0	0.0	0.0	0.0	0.0	62.5	0.0	0.0	0.0
OS	14.1	21.5	0.0	14.1	1.1	15.3	2.3	24.9	5.6	0.0
OL	4.3	69.6	0.0	0.0	0.0	0.0	0.0	26.1	0.0	0.0
OC	0.0	8.3	0.0	0.0	20.8	0.0	0.0	70.8	0.0	0.0
SLD+	0.3	13.0	0.0	13.2	29.3	27.6	13.2	0.0	3.4	0.0
CLD+	5.0	10.0	0.0	0.0	0.0	16.7	23.3	0.0	45.0	0.0
SDC+	20.1	63.6	0.0	8.4	2.9	1.4	0.0	0.0	3.6	0.0
SLC+	0.3	18.3	0.0	14.8	22.1	26.8	12.0	0.0	5.7	0.0
CLC+	2.6	5.1	0.0	0.0	0.0	8.5	35.9	0.0	47.9	0.0
SDB+	36.5	50.8	0.0	5.6	1.4	2.7	0.0	0.0	3.0	0.0
SLB+	2.1	16.3	0.0	9.9	30.6	31.1	7.1	0.0	2.9	0.0
CLB+	1.5	3.1	0.0	0.0	2.6	22.1	21.0	0.0	49.7	0.0
OSCA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0
SDCA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0

Table 3(b)

RESIDUAL SHEAR STRENGTH PARAMETERS

Lithology	Numeric Abbreviation	Number of Samples	Coefficient of Friction, tanϕ		Mean Friction Angle	Cohesion, C (psi)	
			Mean	S.D.		Mean	S.D.
Wilcox Sand	1.0 W	10	0.523	0.048	27.6°	-0.2	0.9
Wilcox Silty Sand	1.2 W	14	0.478	0.009	25.5°	2.1	2.8
Wilcox Clayey Sand	1.3 W	0					
Wilcox Silt	2.0 W	7	0.490	0.059	26.1°	2.4	1.3
Wilcox Sandy Silt	2.1 W	11	0.439	0.029	23.7°	2.6	2.5
Wilcox Clayey Silt	2.3 W	9	0.462	0.033	24.8°	2.3	3.0
Wilcox Clay	3.0 W	6	0.336	0.035	18.6°	3.7	2.7
Wilcox Sandy Clay	3.1 W	0					
Wilcox Silty Clay	3.2 W	17	0.382	0.031	20.9°	4.0	2.2
Carrizo Sand	1.0 C	3	0.510	0.052	27.0°	2.5	0.4
Carrizo Silt	2.0 C	0					
Carrizo Clay	3.0 C	0					
Lignite*	4.0	2	0.622	0.059	31.9°	5.6	4.3
Carbonaceous Material*	5.0	1	0.340	0.000	19.1°	14.2	1.7
Hardstreak*	6.0	--	0.523	0.048	27.6°	0.0	0.9
Alluvial Sand*	1.0 A	4	0.510	0.052	27.0°	2.5	0.4
Alluvial Clay*	3.0 A	4	0.282	0.068	15.7°	3.9	1.0

*Test results from slope stability studies at Phillips Coal Company's Oxbow Project.

Table 3(a)
PEAK SHEAR STRENGTH PARAMETERS

Lithology	Numeric Abbreviation	Number of Samples	Coefficient of Friction, tanϕ		Mean Friction Angle	Cohesion, C (psi)	
			Mean	S.D.		Mean	S.D.
Wilcox Sand	1.0 W	10	0.564	0.049	29.4°	0.3	0.9
Wilcox Silty Sand	1.2 W	14	0.548	0.007	28.7°	4.3	3.9
Wilcox Clayey Sand	1.3 W	0					
Wilcox Silt	2.0 W	7	0.639	0.068	32.6°	6.0	4.0
Wilcox Sandy Silt	2.1 W	11	0.534	0.011	28.1°	7.6	7.1
Wilcox Clayey Silt	2.3 W	9	0.509	0.001	27.0°	10.3	6.4
Wilcox Clay	3.0 W	6	0.470	0.015	25.2°	6.3	6.4
Wilcox Sandy Clay	3.1 W	0					
Wilcox Silty Clay	3.2 W	17	0.475	0.039	25.4°	12.7	5.2
Carrizo Sand	1.0 C	3	0.496	0.009	26.4°	10.3	8.7
Carrizo Silt	2.0 C	0					
Carrizo Clay	3.0 C	0					
Lignite*	4.0	2	1.480	0.109	31.9°	5.6	4.3
Carbonaceous Material*	5.0	1	0.540	0.003	28.4°	46.6	0.8
Hardstreak*	6.0	--	0.663	0.000	33.5°	56.0	0.0
Alluvial Sand*	1.0 A	4	0.681	0.029	34.2°	0.9	0.6
Alluvial Clay*	3.0 A	4	0.307	0.048	17.1°	4.0	1.8

*Test results from slope stability studies at Phillips Coal Company's Oxbow Project.

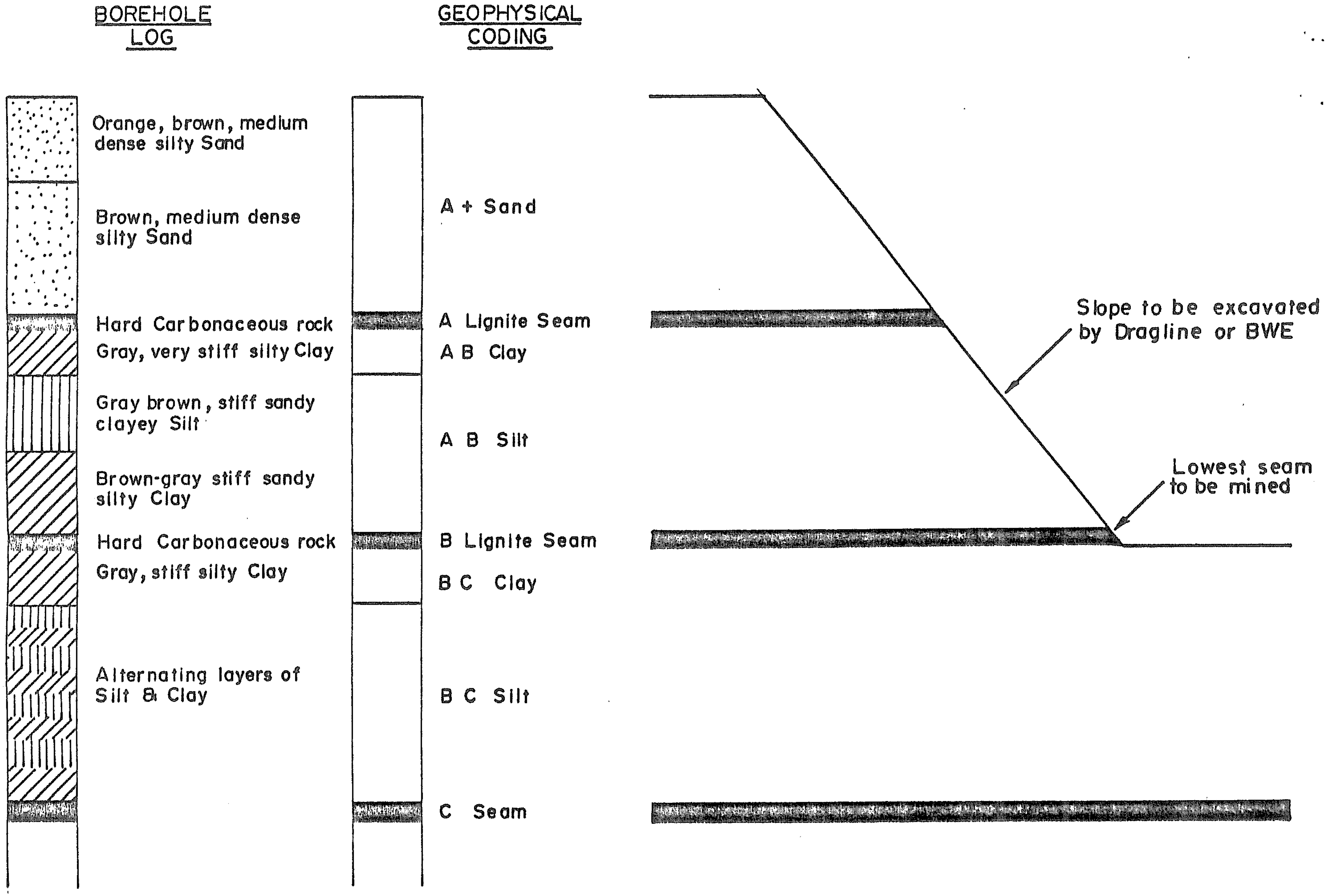

FIG. I REPRESENTATIVE SLOPE AND STRATIGRAPHY

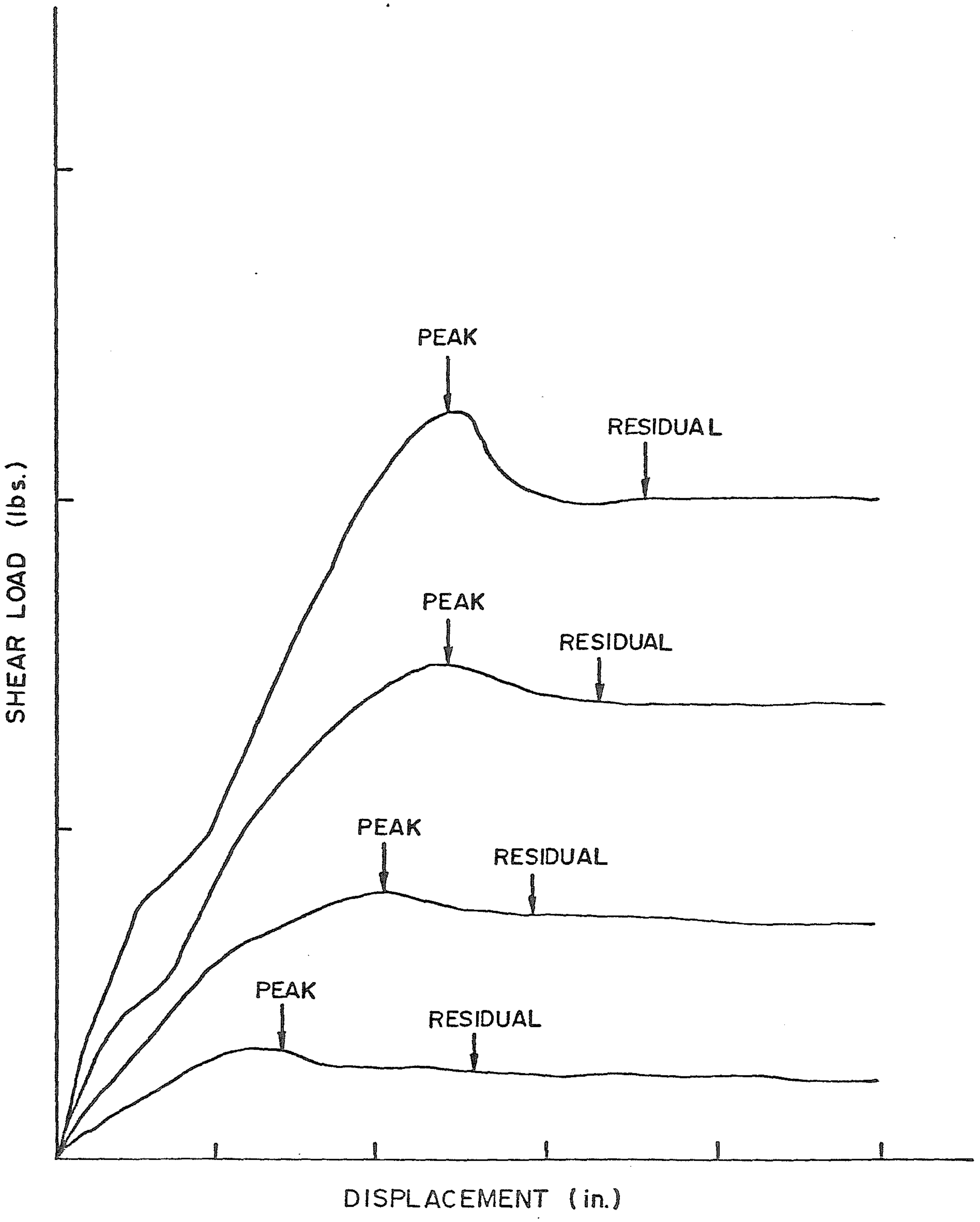

FIG. 2 SHEAR LOAD vs. DISPLACEMENT GRAPH FOR FOUR NORMAL LOADS

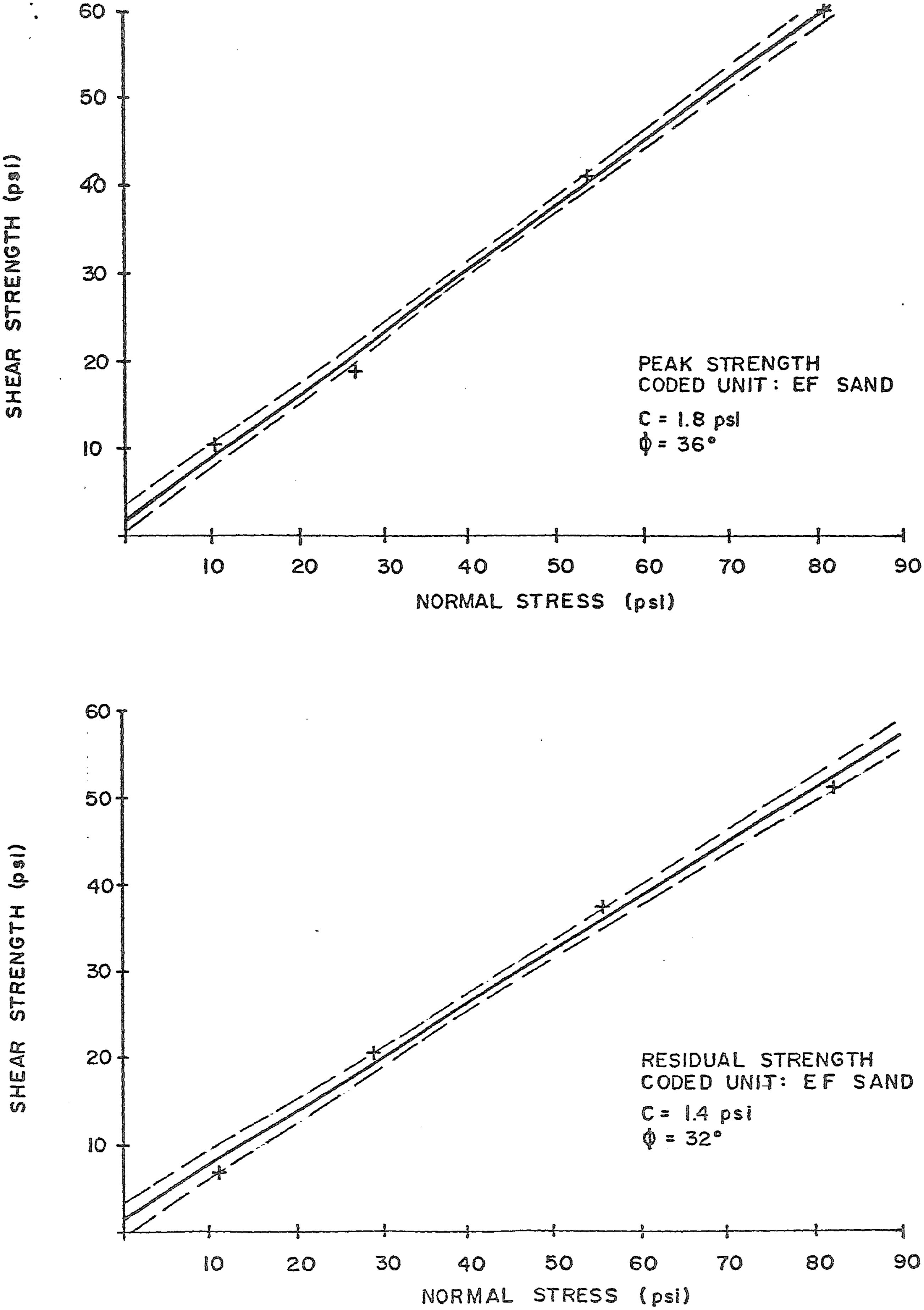

FIG. 3 SHEAR STRENGTH OF SAND

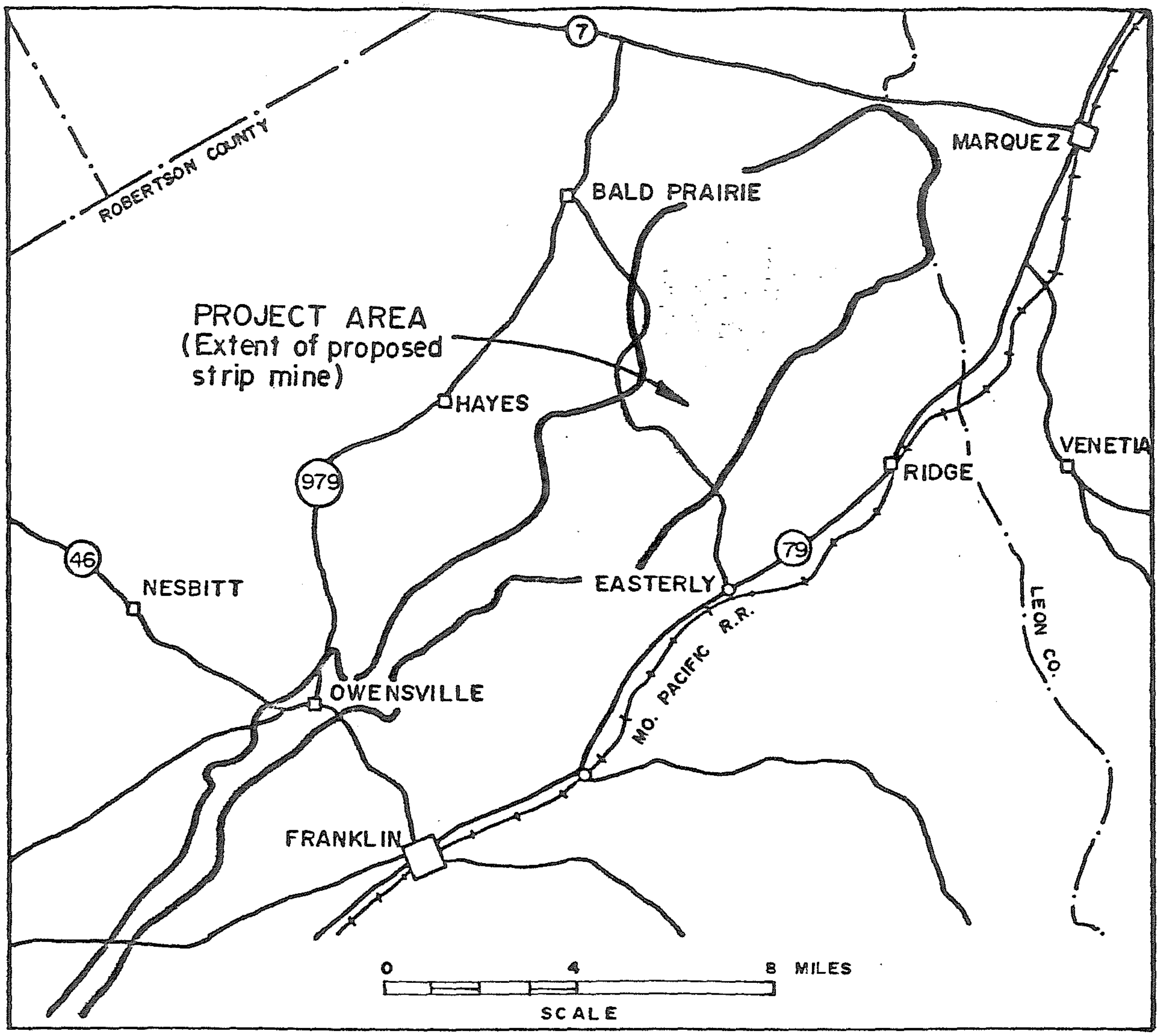

FIG. 4 COLE CREEK PROSPECT VICINITY MAP

ERA	EPOCH	FORMATION	GROUP	
CENOZOIC	EOCENE	Queen City	Claiborne	
		Reklaw		
		Carrizo		PRESENT AT COLE CREEK
		Calvert Bluff	Wilcox	
		Simsboro		
		Hooper		
		Wills Point	Midway	
		Kincaid		
MESOZOIC	CRETACEOUS		Gulf Series	
			Comanchean Series	

FIG. 5 STRATIGRAPHIC COLUMN OF FORMATIONS PRESENT AT THE COLE CREEK PROJECT AREA AND THE SURROUNDING REGION

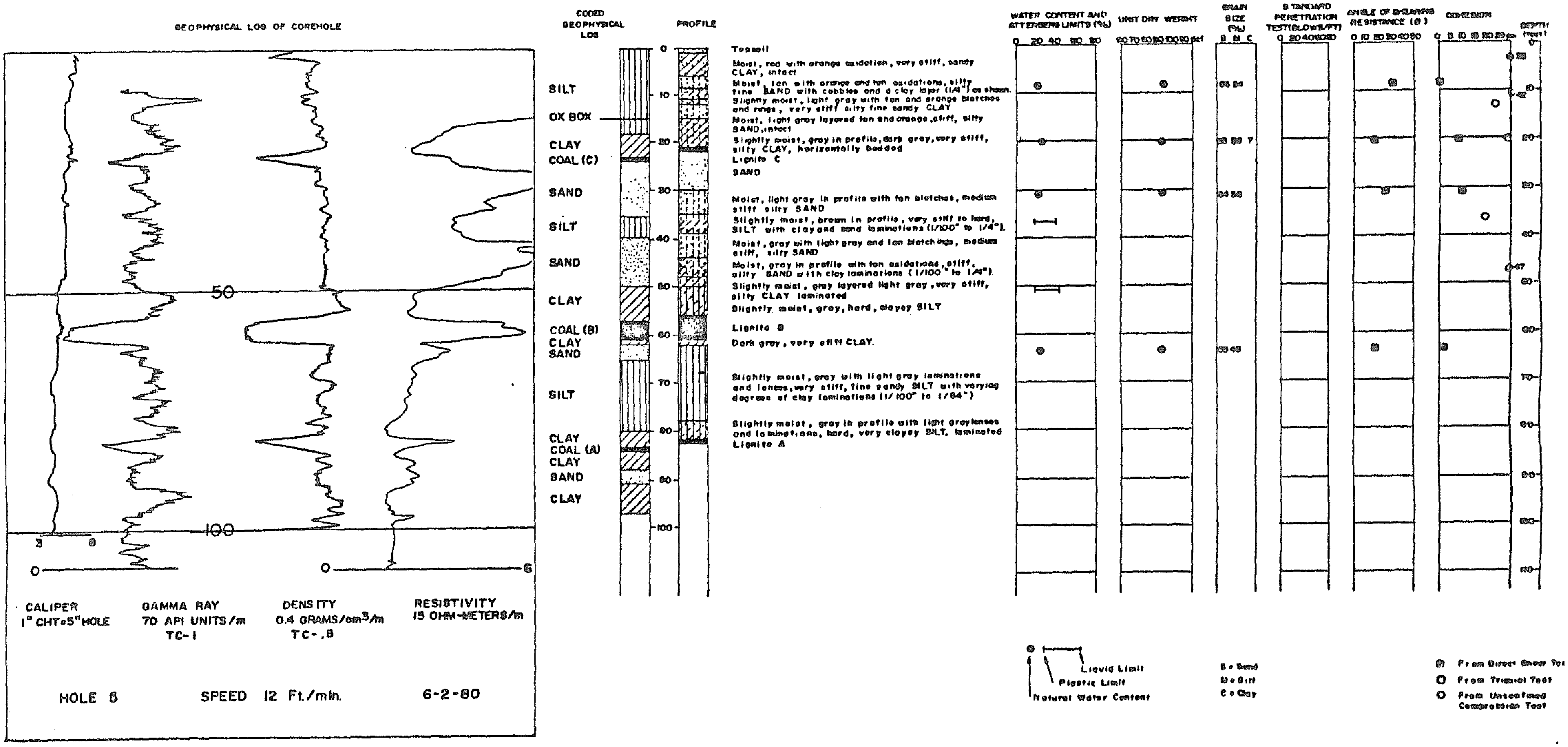

FIG. 6 REPRESENTATIVE BOREHOLE LOG