process; as new observational data become available, they should be used to update the mathematical model.

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Predictions of Pore-Water Pressure and Soil Suction Conditions in Road Cut Slopes in St. Lucia, West Indies: A Methodology to Aid Cut Slope Design

M. G. ANDERSON and P. E. KNEALE

ABSTRACT

There is evidence in the tropics that soil suction may play a most significant role in slope stability. In many developing areas of the tropics, relatively rapid assessments of both road alignment and road maintenance frequently have to be made. A prediction capability is sought for soil suction in selected residual soils of relevance to road cut slopes in St. Lucia, West Indies, and the topographic, material, and precipitation controls on the soil suction are established. It is shown that a dummy variable regression model employing material permeability, precipitation, and qualitative site factors provides good estimates of the recorded soil suction. In addition, the variable importance of three-dimensional slope topography on soil suction is identified. Failures logged during the study period conform to the high-risk sites estimated by the soil suction prediction model. The low site investigation requirement combined with the accuracy of soil suction prediction render such a procedure of potential use to road design and maintenance in tropical areas where only limited geotechnical investigations are possible.

There is mounting evidence within the tropics that soil suction might make a significant contribution to slope stability. Sweeney and Robertson (1), for example, stated that although the influence of soil suction on soil strength has not yet been quantified, there is the likelihood that soil suction contributes to soil strength, especially in the finer-grained soils. More recently, Ho and Fredlund (2, pp. 263-295) were able to demonstrate with a single triaxial test the increase in strength due to soil suction. In addition, they remark that there is no reason to expect a reduction in suction during rain-

fall where there is extensive surface protection against infiltration and the groundwater is below the toe of the slope. Adequate surface protection in this context may be either vegetation or "chunam" protection as used in Hong Kong, for example. The need for studying soil suction in tropical latitudes has been reaffirmed by Brand (3,pp.89-143), who reported that theoretical factors of safety for stable slopes in residual soils are not infrequently less than unity. However, this error in analysis does not have a unanimously agreed-on interpretation. Certain workers argue that the error is due to the neglect of the contribution of soil suction to shear strength, whereas others argue that minimum values of soil suction cannot be realistically or readily assessed in the field and subsequently used for design purposes. Studies undertaken in Hong Kong have, however, shown that suction pressures act as modified effective stresses in that a matrix suction of (Ua - Uw) increases the shear strength by (Ua - Uw) tan ϕ^b, where ϕ^b is the angle of internal friction with respect to matrix suction (3,4), Ua is the pore-air pressure, and Uw is the pore-water pressure.

Parallel to the preceding investigations concerning the relationship between suction and soil strength, there have been a small number of studies determining field suction values in tropical or subtropical latitudes. Sweeney (5, pp.12-23), for example, reports the results of a study in which soil suction determinations were made to a depth of 38 m through a concrete-lined pit wall (caisson) within decomposed granite in Hong Kong in an attempt to establish whether suction could be maintained at such depths during the wet season. In Hong Kong, as elsewhere in the tropics, there is the strong possibility that suction provides a significant contribution to slope stability. In the Hong Kong study, it is of note that the residual volcanic soils with a permeability greater than 5×10^{-5} m s^{-1} always exhibited suction during the reported period at depths commensurate with previous shallow failures.

In the overall contribution of soil suction to the hydrological and strength behavior of slopes, there are four important aspects (6):

1. The possibility of a significant and sustained stabilizing effect on hill slopes; this contribution will likely vary according to grain size as has been noted earlier;
2. Establishment of whether minimum suction occurs simultaneously over significant areas; the effect of likely field variability in the controlling factors of soil water-retention curves and permeability makes this a most important aspect, especially in the context of strength mobilization [Nielsen et al. (7) review spatial variability of soil water properties];
3. The water infiltration pattern, both vertically and laterally; and
4. The timing and magnitude of groundwater recharge by the infiltration process under conditions of either maintained soil suction or partial saturation.

Soil water conditions are not especially well documented in areas of the world experiencing a tropical climate and yet some of the more acute problems of slope stability are known to occur in such areas. In addition, even less attention has been paid to the prediction of soil suction and pore pressures, despite the potential utility in the calibration of shear strength models for slope design, as has been noted previously. The impact of control variables on soil suction has received even less attention.

In this paper it is recognized that there is a need in many developing areas in the tropics to be able to make relatively rapid assessments of either road alignment (8) or road maintenance proposals. Initial coarse grouping of slide behavior and environmental factors can be made with some success, using Landsat and other remote-sensing methods [e.g., a joint project between the Indonesian Road Research Institute and the Transport and Road Research Laboratory in Indonesia and Brand (3) have illustrated slide mechanics and geotechnical risk can be assessed by terrain classification methods].

However, it is evident that relatively little attention has as yet been focused on methods for predicting slope soil-water conditions with the same prerequisite of ease of estimation and an establishment of response categories for topography, soil type, and rainfall. Rectification of this situation is sought by the construction of a methodology for examining soil-water conditions that will facilitate the enhancement of the existing methods for predicting landslide risk for road alignments in the tropics. The assessments in this paper, although based on empirical work in St. Lucia, West Indies, may well be appropriate for other regions, as least as far as the methodology and techniques are concerned.

EQUIPMENT FOR MONITORING SOIL SUCTION AND PORE PRESSURE

It has already been stressed that in many residual soils substantial negative pore-water pressures can develop. Any method of monitoring pressures must therefore take account of this condition, and it is desirable to be able to record both negative and positive pressures. Accordingly a portable hand-held transducer unit was designed that could be carried to each site; the transducer read line was coupled to a zero-volume change tap that terminated the hydraulic read line from a 1-bar ceramic pot buried at the selected depth. The transducer used was differential (-100 to +200 kPa).

In addition, an automatic and continuously recording unit has been designed (Figure 1). In this configuration, 22 sensors can be scanned by a scanivalve fluid switch, the output from which goes to a single transducer and a microprocessor-based data logger. Such a system was used by the senior author for part of the extensive midlevels study in Hong Kong, where monitoring of soil suction and pore pressure was undertaken in 1980-1982 (9). The in-

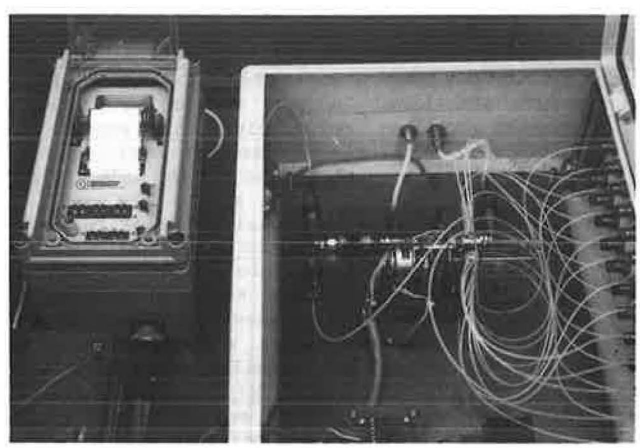

FIGURE 1 Automatically and continuously recording tensiometer system (scanivalve enclosure on the right), microprocessor control, and recording unit.

strumentation has thus been well tested in tropical conditions. [The authors have published a full review of instrumentation for monitoring of soil suction and pore pressure in the tropics (10).]

DEVELOPMENT OF PREDICTION MODELS FOR SOIL SUCTION AND PORE PRESSURE

Data Acquisition

The empirical work was undertaken on the Caribbean island of St. Lucia, West Indies. Within St. Lucia, nine sites were selected for the monitoring of soil water pressures (Figures 2 and 3 and Table 1). A daily monitoring program was undertaken for much of the wet season in 1978 and 1979. In Figure 4 the nature of soil water potentials that typically occur in response to precipitation is shown. The monitoring depth at all sites was 60 cm, corresponding to the depth of failures occurring on the road cut slopes (e.g., Figure 5, site 2 in Figure 3).

Plotting the results of the worst soil water potentials for 40 storms for the sites grouped by permeability results in the clear associations shown in Figure 6. These preliminary findings strongly suggested that a parsimonious statistical model could be established for soil water potential (Ψ) at 60-cm depth at the slope base as a function of rainfall and site characteristics (topography and permeability).

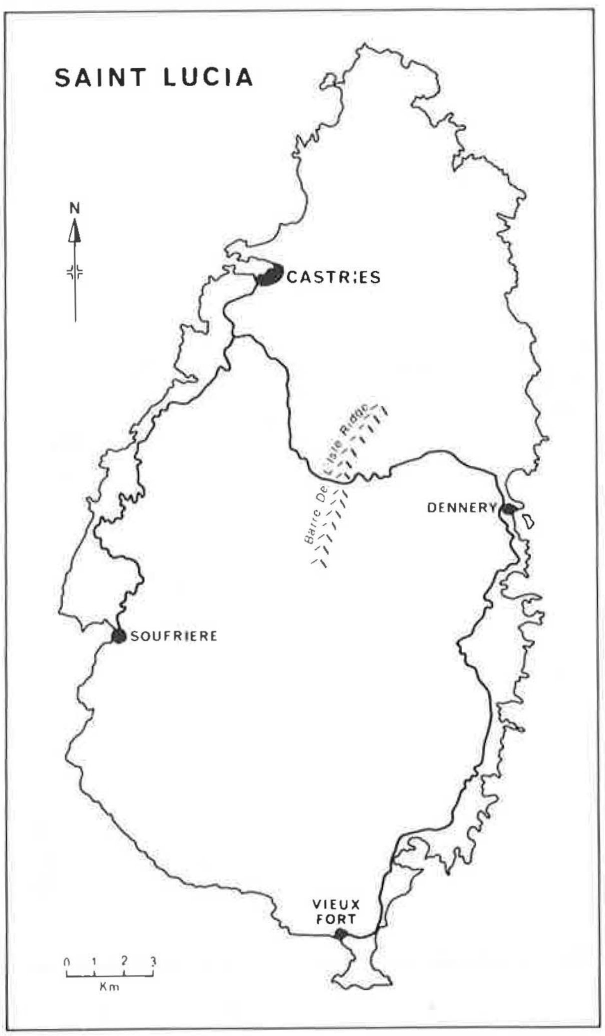

FIGURE 2 Study site location.

Dummy Variable Regression Methods

Of course, standard multiple regression techniques could be calibrated to predict pore pressure from permeability, topography, rainfall, and other variables thought appropriate. However, in terms of the relatively short time available for site investigations in the tropics and the sparsity of laboratory testing facilities, it may be more relevant to contemplate the additional inclusion of qualitative site descriptions. Such a possibility is afforded by dummy variable multiple regression.

This procedure involves the assignment of each site to a group, the characteristics of which are defined by the investigator and may be both qualitative and quantitative. Table 2 shows the basis of the grouping of the nine sites on the grounds of permeability and topography. Formally, then, dummy variables $D_i, i = 1, g$ (g groups) are defined such that that D_i is 1 for group i and 0 for all other groups.

The general regression model then has the form of the following equation in the relationship between storm precipitation and soil-water potential (assuming n observations):

$$\Psi_{60_t} = a_1 + \sum_{i=2}^{g} (a_i - a_1) D_i + \beta_1 X_i + \sum_{i=2}^{g} (\beta_i - \beta_1) D_i X_i \qquad (1)$$

where

$t = 1, n,$

Ψ_{60_t} = soil water potential at 60-cm depth, and

a_1 = intercept of the base group.

The $g - 1$ remaining $(a_i - a_1)$ values are interpreted as differences from this base group. The gradient values (β_i) are similarly interpreted.

When calibrated from the available 82 observations, the equation had the following form:

$$\Psi_{60} = -36.36 - 9.99D_1 - 180.21D_2 - 109.69D_3 + 57.53D_4 + 0.56p$$
$$- 012D_1p + 0.60D_2p + 0.65D_3p - 0.30D_4p \qquad r^2 = 90.6 \text{ percent} \quad (2)$$

which is significant at the $P = 0.001$ level, where p is the storm precipitation.

Thus to predict Ψ_{60} for sites 6, 8, and 9 (base group), D_1 to D_4 = 0 (Table 2), the equation reduces to

$$\Psi_{60} = -36.36 + 0.56\ p \qquad (3)$$

To predict Ψ_{60} for sites 4 and 5 ($D_3 = 1$; $D_1 D_2 D_4 = 0$) the equation reduces to

$$\Psi_{60} = -36.36 - 109.69 + 0.56p + 0.65p \qquad (4)$$

In Figure 6 measured and predicted values for this model (Equation 2) are plotted. This formulation uses the relatively easily determined site parameters of storm precipitation and site topography inspection to predict pore-water pressures. Further, such a model is capable of including more groups with characteristics differing from those defined in Table 2. Thus, in general terms, prediction for a specific site relies solely on deciding in which group it should be placed. This simple procedure then is sufficient to define the form of the prediction model and provide the estimated pore-water pressures for the selected storm precipitation.

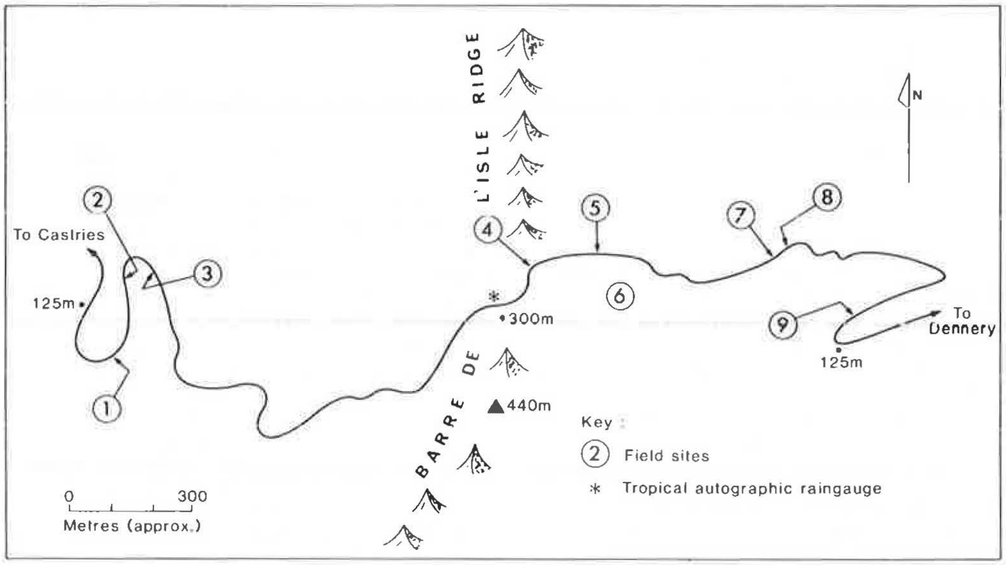

FIGURE 3 Study site location: detail.

TABLE 1 Site Material Properties

Site No.	Material	Angle of Cut Slope (degrees)	Permeability (cm s^{-1})	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index
1	Weathered andesite	54	1.77×10^{-3}	33	–	–
2	Strongly weathered andesite	48	1.80×10^{-3}	40	–	–
3	Strongly weathered andesite	60	2.21×10^{-3}	40	–	–
4	Strongly weathered andesite	60	1.25×10^{-4}	52	44	8
5	Strongly weathered andesite	41	9.03×10^{-5}	52	44	8
6	Strongly weathered andesite	35	5.0×10^{-4}	56	48	8
7	Weathered andesitic breccia	55	2.00×10^{-7}	68	52	16
8	Weathered andesitic breccia	23	2.5×10^{-5}	68	52	16
9	Massive flow deposit	28	3.29×10^{-6}	47	35	12

Testing of Dummy Variable Model

The dummy variable model (Equation 1) was calibrated from data obtained in the period October 1978 through October 1979 (Equation 2, Figure 7). With the additional data obtained in the following 12-month period to September 1980, it was possible to test the model independently. Estimates for the 1980 storm data made in this manner are shown in Figure 8, and the associated distribution of errors ($\hat{\sigma}$ = 32.02 cm water) is shown in Figure 9.

CONTROLS ON SOIL SUCTION

Relative Importance of Topography

The dummy variable regression procedure provides a relatively parsimonious method of estimating basal soil water conditions for a range of materials. However, it is especially useful to attempt a dissection of that model to ascertain the exact control that topographic slope characteristics exert on soil water potential. To this end, three permeability groups were established (10^{-3}: 5×10^{-4} to 5×10^{-3}; 10^{-4}: 5×10^{-5} to 5×10^{-4}; and 10^{-6}: 9×10^{-7} to 5×10^{-5}).

For each permeability group, with Ψ as the dependent variable, multiple regressions were run for precipitation and each of the three topographic indices [slope plan curvature (C) positive concave, downslope length (L), and slope angle (A)] as independent variables. Although prediction relationships for each of the three topographic indices are significant, C has the highest overall explained variance in the three permeability groups. The respective prediction equations for each saturated permeability group are as follows:

K: 1×10^{-3} cm s^{-1}

$$\Psi = -165.78 + 0.75P + 3.08C \qquad r^2 = 87 \text{ percent}, \ n = 47 \qquad (5)$$

K: 1×10^{-4} cm s^{-1}

$$\Psi = -136.15 + 0.72P + 1.69C \qquad r^2 = 70 \text{ percent}, \ n = 36 \qquad (6)$$

K: 1×10^{-6} cm s^{-1}

$$\Psi = -31.83 + 0.45P + 0.54C \qquad r^2 = 62 \text{ percent}, \ n = 51 \qquad (7)$$

It is clear that the effect of C on Ψ increases in the more permeable materials. By contrast, for material with permeability of 10^{-6} cm s^{-1} there are relatively smaller changes in Ψ for given changes in C.

For a 150-mm storm in material of permeability 1×10^{-3} cm s^{-1}, C of +30 degrees (strongly concave) gives Ψ = +39 cm, whereas C of 30 degrees (convex) gives Ψ = -146 cm. Corresponding conditions for material of permeability 1×10^{-6} cm s^{-1} predict Ψ = +52 and +19 cm, respectively.

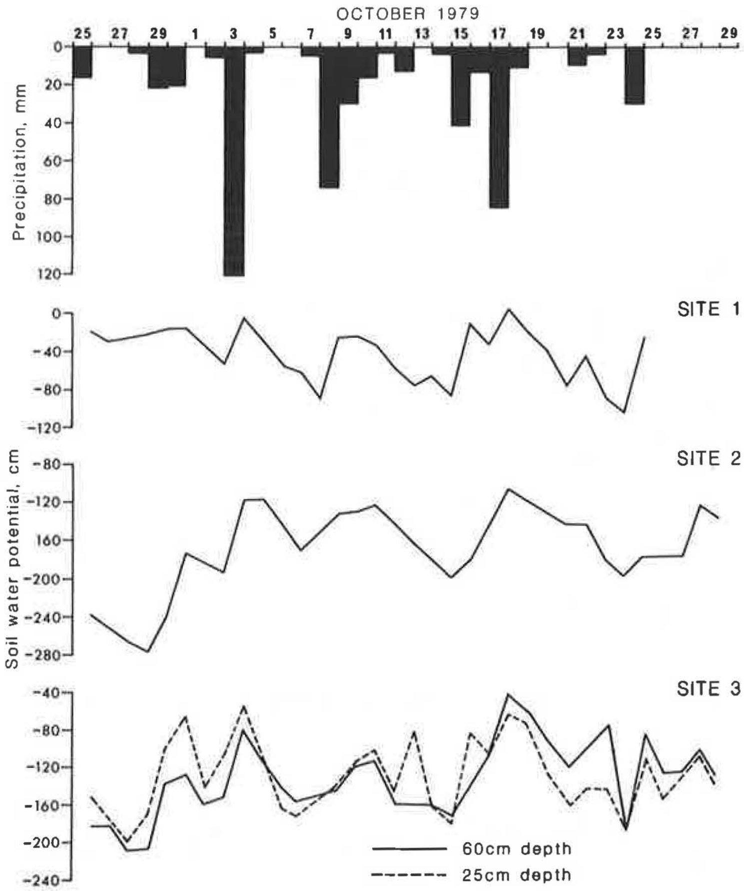

FIGURE 4 Soil water potential responses to precipitation.

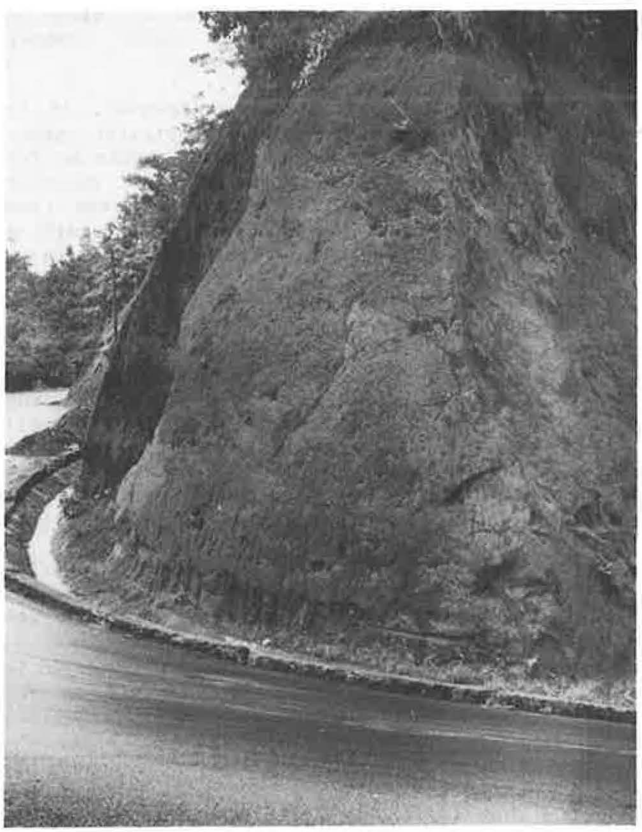

FIGURE 5 Site 2.

By the use of beta weights, it is possible to assess the relative importance of topography in relation, say, to precipitation, as affecting pore pressures in a range of different materials. Thus more substantive comparisons than those made by the multiple regression methods described previously are possible. Beta weights indicate how much change in the dependent variable is produced by a standardized change in one of the independent variables when the others are controlled. In the standard notation $\beta ij \cdot k$, variable i is being predicted from variable j with the effect of variable k controlled. The direct utility of this procedure is that it is possible to assess the effect of changes in slope topographic elements (A and C) on soil water potential separately from similar changes in precipitation. Moreover, this analysis can be undertaken for each of the permeability groups to ascertain whether there is any change in the relative effects of A, C, and P (the independent variables) on Ψ.

Figure 10 shows the generalized relationships of beta weights for different controlled variables (A, C, and P) for each permeability group. The two main points from this analysis are as follows:

1. For high permeability (10^{-3} cm s^{-1}) slope plan curvature exerts as great an effect on soil water potential ($\Psi C \cdot P$ at 10^{-3} cm s^{-1} = 0.68) as precipitation does ($\Psi P \cdot C$ at 10^{-3} cm s^{-1} = 0.63) and

2. For less permeable material (1×10^{-6} cm s^{-1}) the relative effect of slope plan curvature on soil water potential diminishes, whereas that of slope angle and precipitation increases.

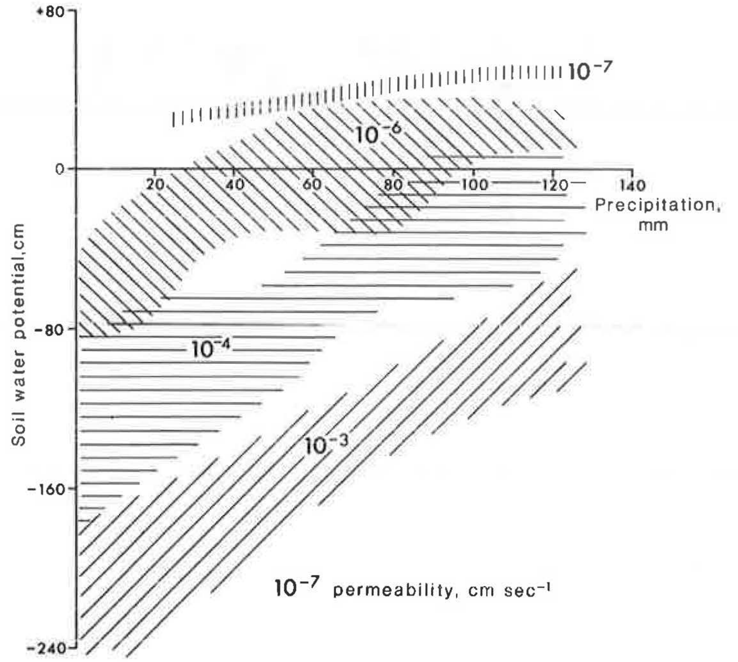

FIGURE 6 Relationship of permeability, precipitation, and soil water potential based on 40 storm events.

TABLE 2 Group Characteristics and Dummy Variable Status for Equation 1

Group	Permeability (cm s^{-1})	Topography	Site	Dummy Variable Status
1	1 x 10^{-3}	Hollow	1	$D_1 = 1; D_2D_3D_4 = 0$
2	1 x 10^{-3}	Straight	2,3	$D_2 = 2; D_1D_3D_4 = 0$
3	1 x 10^{-4}	Straight	4,5	$D_3 = 1; D_1D_2D_4 = 0$
4	1 x 10^{-7}	Straight	7	$D_4 = 1; D_1D_2D_3 = 0$
Base	1 x 10^{-4}	Straight	6,8,9	D_1 to $D_4 = 0$

Predicting Mean Annual Frequency of Pore-Water Pressure

Having predicted the values of Ψ_{60} at the base of the nine cut slope sites (Figures 8 and 9), it is desirable to attempt an estimate of the mean annual frequency with which given pore-water pressures will occur in the different materials monitored.

Of course, an overriding restriction here is that values of Ψ_{60} cannot practically be obtained on a daily basis at all sites for a large number of years. It therefore becomes necessary to seek a surrogate mean frequency distribution to which such data can be tied. For the Windward Islands there are available precipitation records at a large number of stations, the data from which have been analyzed in the specific context of mean annual frequency (days) of the occurrence of specific precipitation totals (e.g., 25, 50, 75, 125 mm). Figure 11 shows just such a relationship for the Barre de l'Isle site together with that for Marquis, a site of much lower elevation to the north (Figures 2 and 3). If it can be assumed that there is an invariant relationship between daily storm precipitation (P_D) and Ψ_{60}, then of course the Ψ_{60} precipitation data can be routed through the relationship in Figure 10 to yield the mean annual frequency (F) of given Ψ_{60} values. It has been shown that for total storm precipitation (P) and Ψ_{60} significant linear relationships exist for all sites (11).

The estimation procedure for relating F, Ψ_{60}, and K is therefore subject to two opposing constraints:

1. Only F values for daily and not total storm precipitation are available, and
2. It may be unrealistic to expect too close an association between all Ψ_{60} and daily (rather than total) storm precipitation values.

With the currently available data, however, it is necessary to circumvent the second constraint rather than modify the precipitation data to obtain an F-P relationship, even if that proved possible (bearing in mind the nonuniform time base of storms from which P is derived). A realistic way of determining the trend of the Ψ_{60}-P_D relationship for each site is to take values of Ψ_{60} at, or close to, the maximum and minimum recorded in association with 24-hr antecedent precipitation (P_D). Intermediate values of Ψ_{60} may be expected to show greater fluctuation, depending on significantly larger antecedent conditions. Qualitative examination of the time series of Ψ_{60}-P_D by Anderson (11) for all sites suggests this to be a reasonable strategy; that is, highest and lowest Ψ_{60} and P_D are in close association and the expectation is that this association will hold irrespective of the conditions in excess of 24 hr before the Ψ_{60} reading. If this is accepted, extreme values of Ψ_{60} and P_D can be used for each site and routed through the relationship of Figure 10 to provide an F-Ψ_{60} relationship for each site.

A further point has to be noted here, which is that because the known F-P_D relationship is for the Barre de l'Isle rain gauge (Figures 5 and 3), individual site P_D-values must be converted to the precipitation at that gauge and these two precipitation values must be assumed to have a common frequency. That is, the general relationship shown in Figure 10 holds for all nine sites in the Barre de l'Isle area; the site precipitation P_D on the or-

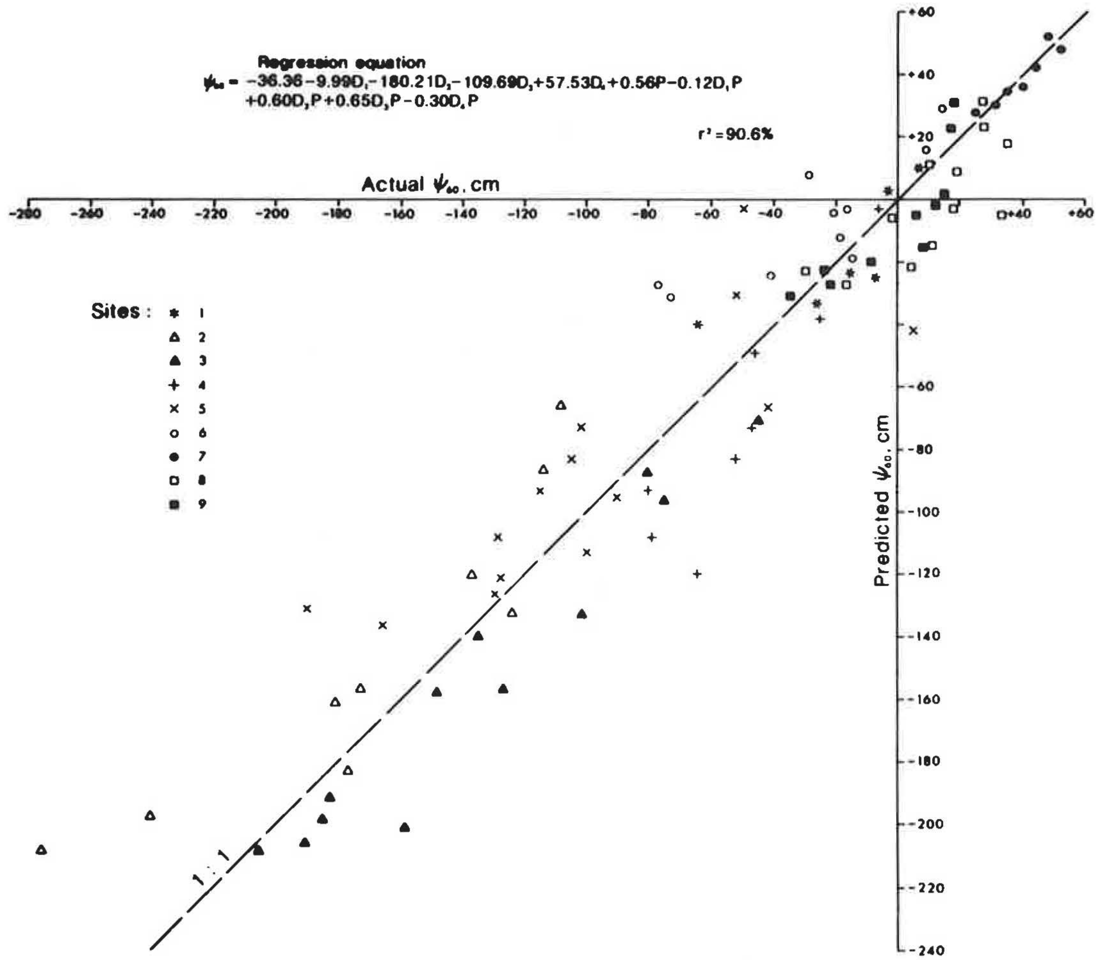

FIGURE 7 Measured and predicted values of ψ_{60}.

dinate is determined by the individual site calibrations to the main Barre de l'Isle rain gauge.

With these constraints, data were obtained for sites 2-8 taking extreme values of Ψ_{60} together with the corresponding P_D-value converted to the equivalent precipitation at the Barre de l'Isle site. This precipitation value was then routed through the following relationship (Figure 11) to provide a frequency value (Table 3, column 4):

$$\text{Log } F = 1.699 - 0.015P_D \tag{8}$$

All 14 values were then subjected to a linear multiple regression analysis employing Ψ_{60} and K to predict F. For the Barre de l'Isle sites, the relationship was significant at the p = 0.01 level:

$$F = -32.20 - 0.22\Psi_{60} - 8.79 \text{ Log } K \quad r = 0.98 \tag{9}$$

This relationship is graphed in Figure 12. Table 3 (column 6) shows the errors from this relationship to be tolerably small with $\hat{\sigma}$ = 6.46 days. Thus, Figure 12 can be used to predict the mean annual frequency F (days per year) with which a given material (of permeability K) will experience a pore pressure Ψ (at 60-cm depth at the slope base).

It is stressed that despite the obvious goodness of fit of Equation 4, this provides a guide to F-values only within the constraints of the adopted methods as outlined. Nevertheless, with the inevitable lack of long-term daily Ψ_{60}-records at all sites, such a method is seen as the only practical means of making an estimation of F for pore-pressure values.

In addition to the Barre de l'Isle site, the F-P_D relationship can also be determined for Marquis (Figures 2 and 3). From available data estimates can be derived of F based on K and Ψ_{60} under conditions of the F-P_D relationships pertaining at Marquis:

$$\text{Log } F = 1.721 - 0.02P_D \tag{10}$$

Thus, Figure 12 shows the estimates of F that result when the Marquis F-P_D relationship is applied to the Ψ_{60}-P_D data found at Barre de l'Isle. Thus because for a given P_D, F is less at the Marquis site than at the Barre de l'Isle site, Figure 12 shows that for given Ψ_{60}- and K-values, the mean frequency of occurrence of that Ψ_{60}-value is significantly less at the Marquis site than at the Barre de l'Isle site; it is given as follows:

$$F = -34.75 - 0.23\Psi_{60} - 8.73 \text{ Log } K \tag{11}$$

Thus, if we assume a spatial commonality of porewater pressure response at the slope base to daily precipitation (extreme values only as already outlined) in the different materials monitored, it is possible to derive the mean frequency of occurrence of a given Ψ_{60} by establishing the spatial variation in F-P_D relationships (Figure 10) only.

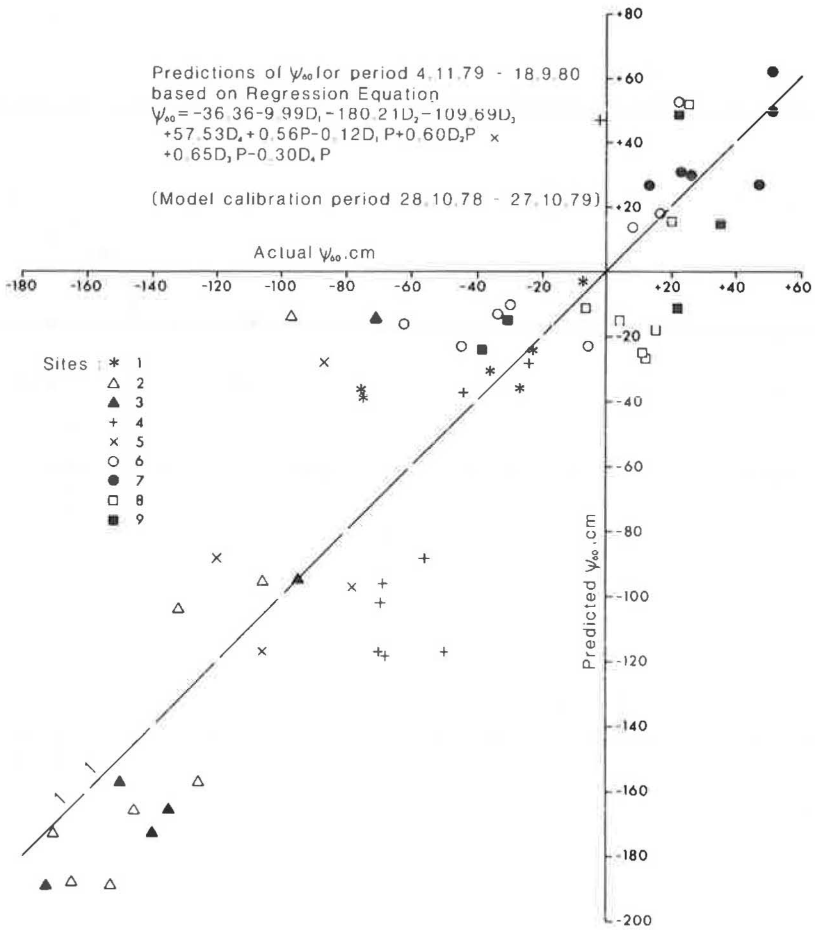

FIGURE 8 Predictions from Equation 2 for independent data on soil water potential.

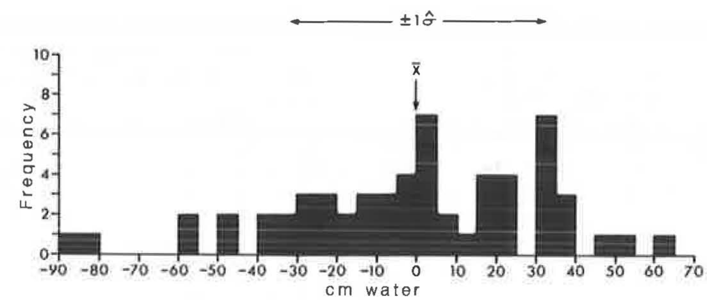

FIGURE 9 Error distribution from Figure 7.

The procedure described and applied here is summarized diagrammatically in Figure 13.

CONTROLS ON FAILURE CHARACTERISTICS

Throughout the duration of the project, a schedule of slope failures was kept. Because the importance of the topographic slope elements has been clearly demonstrated in the context of soil water potential control, it is possible to plot failed and stable sites by permeability group, noting for each site the prefailure slope angle, slope plan curvature, and material strength. Permeability group, slope angle, and curvature are sufficient to specify soil water potential conditions [Equation 2 (11)] for given storm precipitations. Figure 14 shows the result of plotting such data by permeability group, distinguishing between slopes stable throughout the study period and those subject to failure. Envelopes are provided discriminating between stable and failed slopes for given penetrometer values at 50 or more sites.

These tentative failure-topography relationships are consistent with the results of the previous discussion (Equations 5-7). For decreasing permeability the principal discrimination is on slope angle, whereas for more permeable material slope plan curvature provides significant discrimination (Figure 14). In addition, for a given slope plan curvature, decreasing material permeability is shown to necessitate increased strength to ensure stability at a

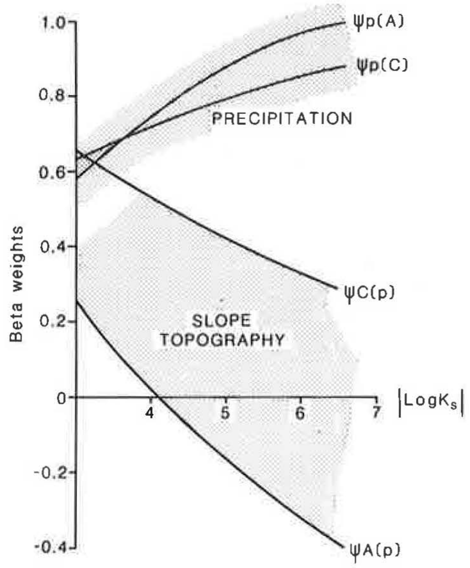

FIGURE 10 Beta weights in selected relationships for different permeabilities.

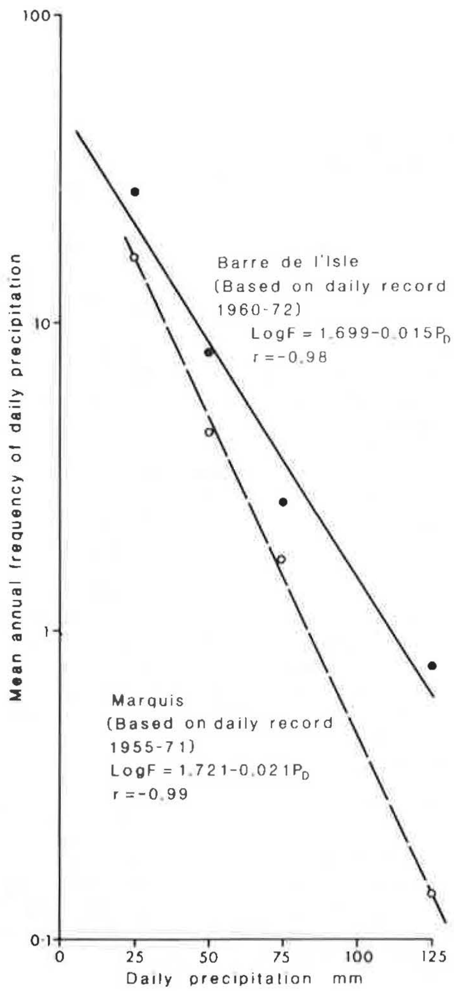

FIGURE 11 Frequency relationships for daily precipitation.

TABLE 3 Predicting Mean Annual Frequency of Occurrence of Pore-Water Pressure: Barre de l'Isle

Site No.	Ψ_{60} (cm water)	Equivalent Site Precipitation at Barre de l'Isle Gauge (mm)[a]	Frequency (days/year)[b]	Predicted Frequency[c]	Errors[d]
2	- 17	100	1.5	13.4	-11.1
	-275	3	45.0	52.9	- 7.9
3	- 45	55	7.4	1.1	+ 6.3
	-205	3	45.0	36.7	+ 8.3
4	- 2	100	1.5	2.7	- 1.2
	- 80	30	18.0	20.0	- 2.0
5	+ 5	45	10.0	2.3	+ 7.7
	-166	3	45.0	40.2	+ 4.8
6	+ 22	100	1.5	8.8	- 7.3
	- 77	13	32.0	30.8	+ 1.2
7	+ 52	52	8.0	15.1	- 7.1
	+ 13	15	29.0	23.8	+ 5.2
8	+ 35	52	8.0	9.3	- 1.3
	- 30	15	29.0	23.8	+ 5.2

[a]Figures 2 and 3.
[b]Equation 3, Figure 11.
[c]Equation 9.
[d]$N = 14$; $\bar{x} = 0.06$; $\hat{\sigma} = 6.46$.

given angle. Strength values shown in Figure 14 are in terms of the field-determined Michigan penetrometer values. These values have a direct relationship to unconfined strength and material consistency (12). Michigan values in excess of 10 correspond to strengths greater than 4.0 kg cm^{-2} (hard consistency); those of 5 to 10 correspond to strengths in the range 2-4 kg cm^{-2} (stiff consistency).

The failure-monitoring program therefore has provided direct evidence (Figure 14) of the empirically determined soil water potential relationships outlined in the foregoing and illustrated in Figures 8-10. Controls on the precise nature of the failed zones (e.g., depth/length ratio of the slip) were much more difficult to ascertain. A mineralogical examination was made of the material at all the failed sites. A qualitative assessment of these results in association with failure form revealed the absence of any mineralogical control. Prior and Ho (13) were able to suggest broad clay mineralogy controls on a range of landslide forms in St. Lucia and Barbados. However, this study suggests that such an association may well not be an association that is robust against the degree of spatial variation in mineralogy as well as slide form that has been observed. In any event, there is no evidence to employ mineralogy in the context of slope failure predictions, it being evident that the major controls useful in a design context are those of slope topography and material permeability, as already outlined.

DISCUSSION

In many underdeveloped tropical areas of the world, there is a substantial degree of activity in road maintenance as well as new construction. Despite this, there are relatively few available methods to aid the engineer in terms of route planning and maintenance. One such method, that of terrain classification, has proved successful to a limited degree (3,8). This study sought to examine the possibility of enhancing preexisting methods by attempting to develop parsimonious models for the prediction of soil water conditions and to identify the dominant controls on such conditions. Such information, even in the absence of strength determinations, which are often an enforced condition in

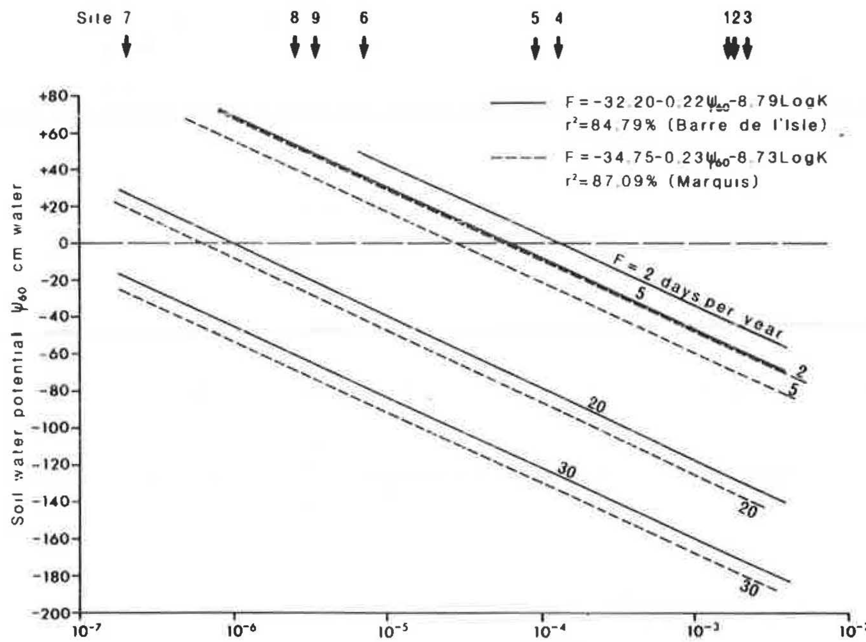

FIGURE 12 Predictions of mean annual frequency (F) of soil water potential in given material permeabilities.

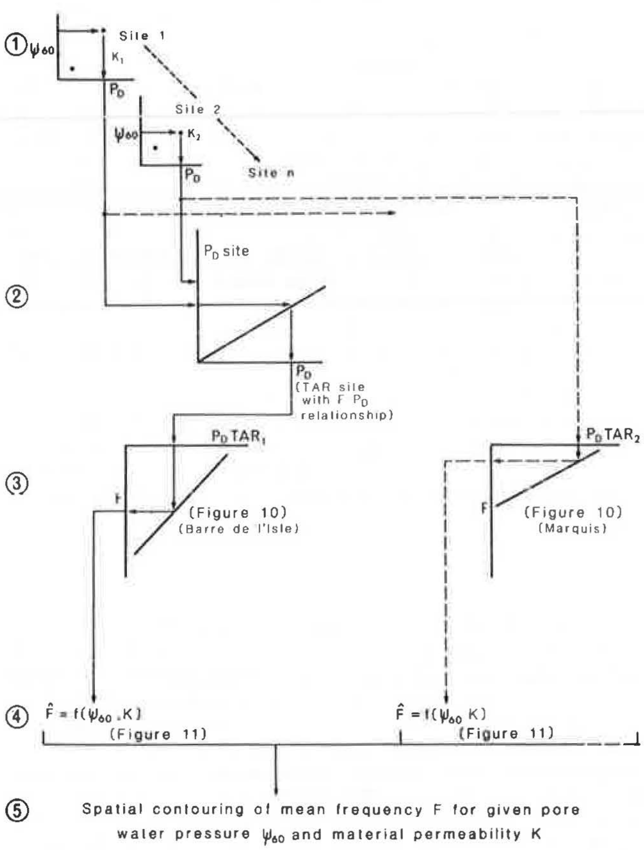

FIGURE 13 Summary of method for estimation of mean annual frequency of soil water potential occurrence.

underdeveloped tropical areas, offers the prospect of improved cut slope design. This study based on the residual volcanic material in St. Lucia (Table 1) has shown

1. That a prediction model can be calibrated for soil water conditions (Equation 2) and has acceptable predictive success tested against independent data (Figure 8);
2. That topographic slope parameters have a variable influence on soil water status dependent on material permeability, slope plan curvature being relatively unimportant for low-permeability material (Equations 5-7, Figure 10);
3. That there is a requirement to predict not only absolute soil water conditions but also their recurrence interval [in this regard a methodology is suggested and, within the assumptions set by the procedure, it is shown to provide a useful adjunct to the soil water prediction models (Figures 12 and 13); unquestionably, this area is one deserving of much greater attention, especially in the context of deeply weathered residual soils]; and
4. That failures logged during the study period could be isolated and grouped according to the dominant criteria identified by the statistical analysis of controls on soil water status. Such a pattern of response (Figure 14) therefore adds additional credence to the likely success of the work reported here as related to aiding road cut slope design under conditions of sparse geotechnical information.

What is generally clear is that there are circumstances, such as those described in this paper, in which soil suction and pore-water pressure can be predicted with acceptable accuracy. In a design context the implication is that such equations (5-7) can then be used as a more dynamic forecasting input to the pore-water term in effective stress equations

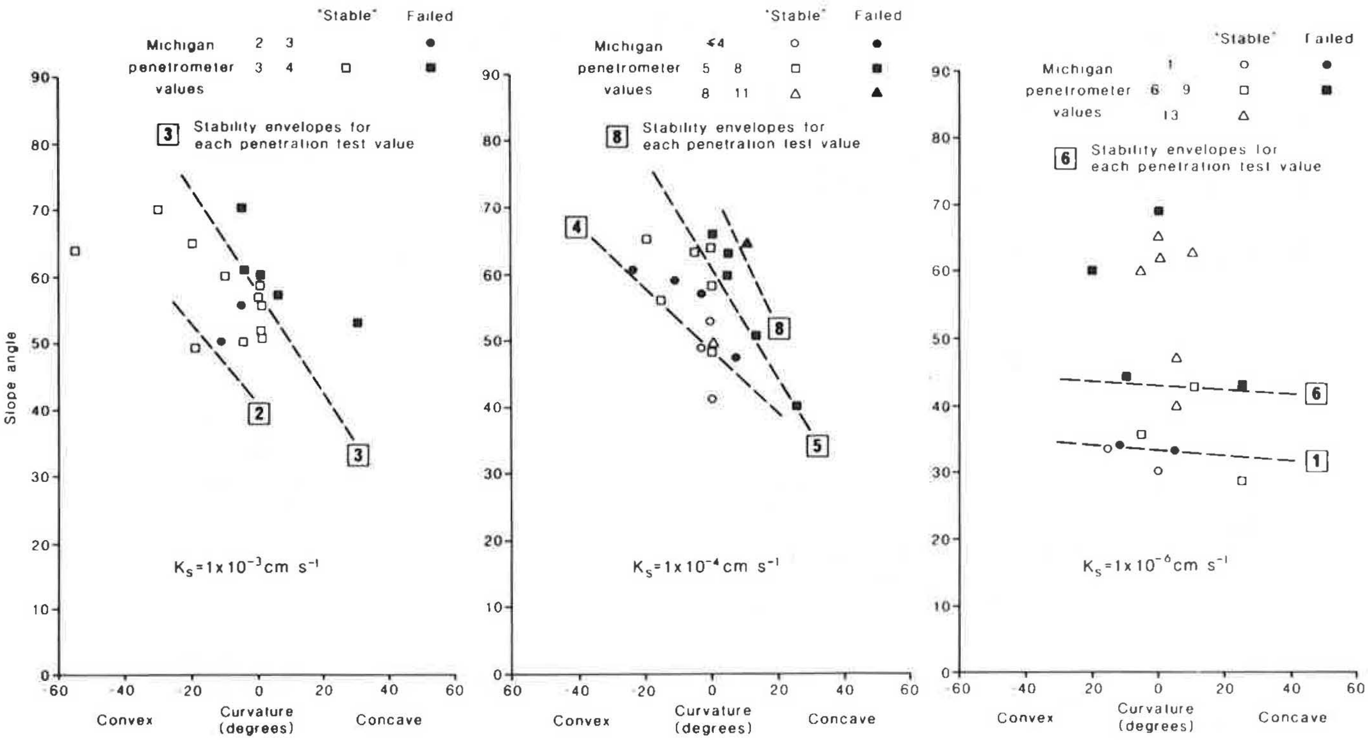

FIGURE 14 Stability envelopes for failures logged on the study section for the three permeability groups.

for slope stability analysis. At a site-specific level, the envelopes shown in Figure 13 represent a general guide to cut slope design in the residual soils of St. Lucia, which may serve to reduce landslide risk associated with planned road development. In particular, they illustrate to the designer the significant impact slope plan curvature can have on stability in the higher-permeability materials.

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