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Increase in Factor of Safety Due to Soil Suction for Two Hong Kong Slopes

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SYNOPSIS

Stability analyses for two cut slopes are presented to show the effects of soil suction on the computed factors of safety. The increase in soil strength due to suction is included in terms of an increased cohesion. The effect of suction on the location of the critical slip surface is also presented.

INTRODUCTION

The effect of negative pore-water pressure on the soil strength has usually not been considered in the stability analysis of slopes. Rather, it has generally been assumed that the negative pore-water pressure will eventually dissipate, resulting in a reduction in soil strength and a decrease in the stability of the slope with time (Widger and Fredlund, 1979). Therefore, stability analyses are usually performed using saturated parameters although the soil in the slope may remain unsaturated. This may lead to a hiatus between the analytical results and actual conditions.

Intense urban developments in Hong Kong have inevitably spread to the nearby hillsides despite encountering perilous conditions. These developments often involve cuts that are designed on the basis of precedent experiences with similar sites. Allowable slopes are relatively steep, often exceeding 45 degrees.

It has been observed that many steep slopes, both natural and cut, are unsaturated. Soil suctions are measurable from the surface to a considerable depth. Slope failures have been common and have frequently occurred during or after periods of heavy and prolonged rainfall. This rainfall causes infiltration and a reduction in soil strength as a result of a loss of suction in the slopes (Lumb, 1975). Back analysis of steep slopes assuming saturated conditions has often shown their factor of safety to be less than 1 (e.g., 0.8). Sweeney and Robertson (1979) concluded that soil suction is a significant factor contributing to the shear strength of the Hong Kong slopes.

In this paper, two cut slopes in Hong Kong are studied to demonstrate the effect of soil suction on their stability. The increase in strength due to soil suction is included in terms of an increase in the cohesion of the soil. The analyses are performed using the General Limit Equilibrium (GLE) method of slices.

THEORETICAL ASPECTS

Fredlund, Morgenstern and Widger (1978) presented the shear strength equation for unsaturated soils written in terms of two stress state variables $(\sigma - u_a)$ and $(u_a - u_w)$.

$$\tau = c' + (\sigma - u_a)\tan \phi' + (u_a - u_w)\tan \phi^b \quad (1)$$

where:
- τ = shear strength of an unsaturated soil,
- c' = effective cohesion,
- σ = total normal stress,
- u_a = pore-air pressure in the soil,
- u_w = pore-water pressure in the soil,
- ϕ' = angle of internal friction with respect to changes in $(\sigma - u_a)$,
- ϕ^b = angle of internal friction with respect to changes in $(u_a - u_w)$,
- $(\sigma - u_a)$ = total stress, and
- $(u_a - u_w)$ = matric suction.

The shear strength equation for an unsaturated soil can be incorporated in a slope stability analysis in a manner similar to that used for a saturated soil. The net result can be presented in either of the following ways.

1. First, the limit equilibrium equations for factor of safety can be re-derived. Equation (1) can be used to represent the soil strength from which the factor of safety can be computed. This approach can readily be applied to the General Limit Equilibrium (GLE) method of slices (Fredlund, Krahn and Pufahl, 1981).

   The equations associated with this modified method of analysis are similar to those for a conventional slope stability analysis. The differences are that the modified equations contain the matric suction term, $(u_a - u_w)$, and that the pore-water pressure, u_w, is substituted by the pore-air pressure,

u_a.

2. Second, the influence of matric suction can be considered as an increase in the cohesion of the soil (Fredlund, 1979). This procedure obviates the need of reformulating the factor of safety equations, and it was adopted in this study. The total cohesion is, therefore, equal to the sum of the effective cohesion, c', and the increase in cohesion due to the matric suction.

$$c = c' + (u_a - u_w) \tan \phi^b \quad (2)$$

where:
c = total cohesion for an unsaturated soil.

DESCRIPTION OF SOIL MATERIALS AND INSITU SOIL SUCTION MEASUREMENTS

The principal surficial materials of Hong Kong are residual soils derived from the igneous rocks, mainly granite and rhyolite. Active weathering processes have resulted in residual soils to a considerable depth in most places. These soils are highly variable owing to the differential weathering processes and the differences in the mineralogy of the parent rocks (Lumb, 1962 and 1965).

The strength properties of the Hong Kong residual soils have been previously investigated (Lumb, 1962; 1965). For coarse to medium-grained granitic soils, the angle of internal friction, ϕ', varied from 35 to 40 degrees whereas it ranged from 20 to 40 degrees for the fine-grained soils. The friction angle, ϕ', for the rhyolitic soils ranged from 30 to 35 degrees. The friction angle tended to increase with the soil density and granularity for both soil types. The cohesive component of strength for both residual soils was variable and was primarily dependent on the degree of saturation. The variation in the cohesion is believed to be more directly related to the effect of soil suction (Fredlund, 1979).

Ho (1981) measured the unsaturated shear strength parameters for both Hong Kong soils using a multi-stage triaxial test. The multi-stage test was used in order to minimize the effect of soil variability. The axis-translation technique was used to maintain various suction values in the soil. The average friction angle with respect to matric suction, ϕ^b, for the weathered granite ranged from 10 to 20 degrees and 11 to 16 degrees for the weathered rhyolite.

In order to include the effect of increased strength due to suction, the matric suction profile for the soil in the field must be known. The matric suction profile can be determined directly by field measurements. Insitu soil suction measurements have been made at several sites in Hong Kong (Sweeney, 1982). The measured matric suction profiles have been observed to vary almost linearly with respect to the distance above the water table. The suction values reached an upper limit of approximately 80 to 100 kPa which is the ultimate capacity of the tensiometer. The suction increased at a rate of 1 to 3 kPa per metre above the water table. This corresponds to approximately 10 to 30 percent of the negative hydrostatic pressure.

Figure 1 illustrates the relationship between the matric suction above the water table and the increase in the cohesion of the soil. An ϕ^b angle of 15 degrees has been used in drawing Figure 1. Various percentages of the negative hydrostatic profile are later used for the analysis, while maintaining a maximum suction value of 100 kPa.

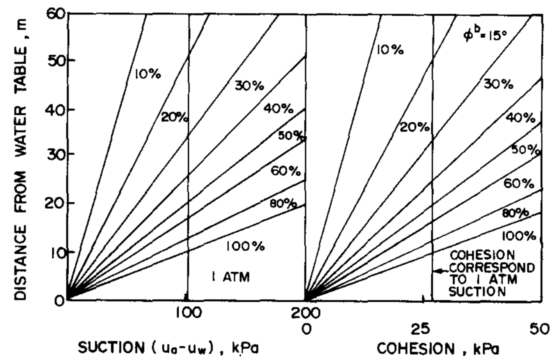

Fig. 1 Variation in Soil Suction and Equivalent Increase in Cohesion

STABILITY ANALYSES FOR TWO STUDY SITES

Study Site 1: Fung Fai Terrace

Fung Fai Terrace is located in the north central part of Hong Kong Island. The site consists of a row of residential buildings as shown in Figure 2. At the back of these buildings is a steep cut slope with an average inclination of 60 degrees to the horizontal and a maximum height of 35 metres. The cutting has been protected from infiltration of surface water by a layer of soil cement and lime plaster (i.e., locally referred to as chunam plaster) and has been in place for more than 40 years. Small but dangerous failures have occurred periodically at the crest of the cut slope and the low calculated factor of safety causes some concern. These circumstances prompted a detailed investigation.

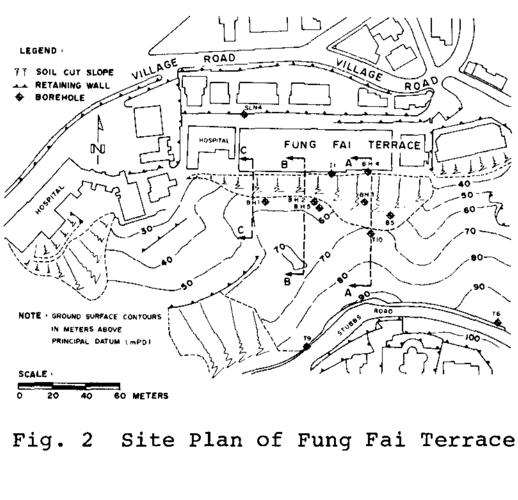

Fig. 2 Site Plan of Fung Fai Terrace

Three cross-sections A-A, B-B and C-C are shown in Figures 3 to 5. The stratigraphy consists primarily of weathered granite. There is a layer of granitic colluvium of 4 to 5 metres thick present at the top of slope. Beneath the colluvium is a layer of completely weathered granite varying from 10 to 20 metres in thickness which is underlain by a layer of completely to highly weathered granite of about 10 metres thick. Bedrock is situated 20 to 30 metres below the surface. The water table is located well into the bedrock. It is estimated that the water table may rise by 5 and 8 metres under the influence of heavy rains with return periods of 10 and 1000 years, respectively. The groundwater level does not directly affect the stability analyses.

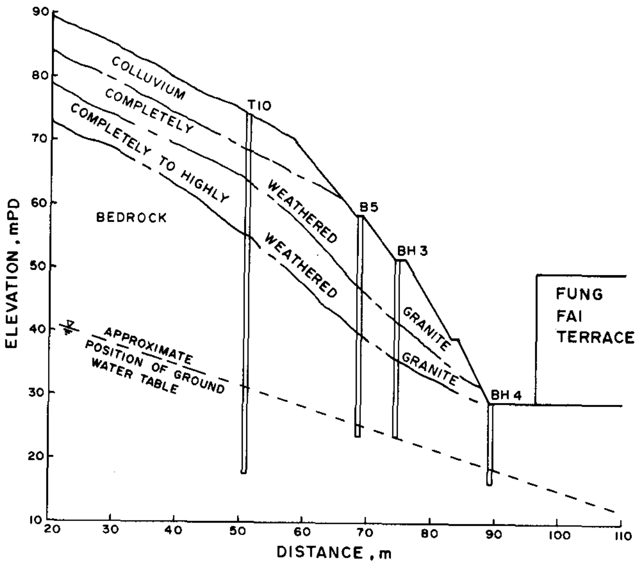

Fig. 3 Section A-A of Fung Fai Terrace

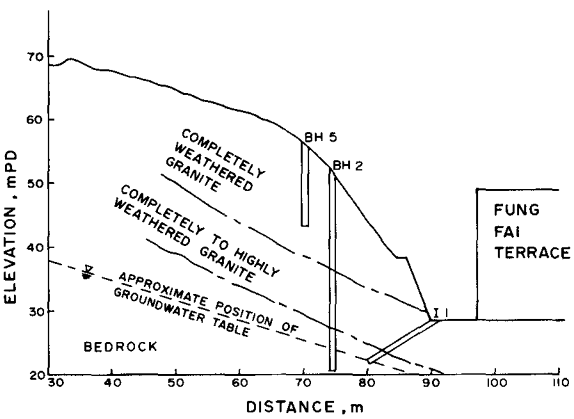

Fig. 4 Section B-B of Fung Fai Terrace

Undisturbed core samples were tested to establish the pertinent strength parameters. Results are given in Table I. The average ϕ^b angle for the soils was taken as 15 degrees (Ho, 1981).

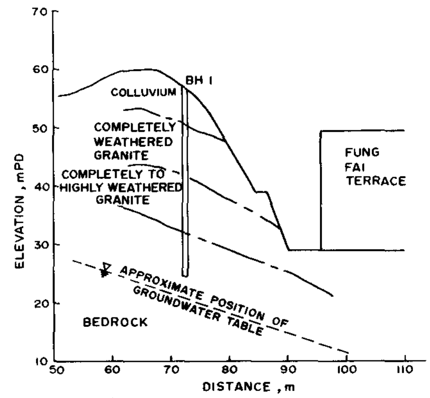

Fig. 5 Section C-C of Fung Fai Terrace

TABLE I

Strength Properties for Soils at Fung Fai Terrace

Soil Type	Unit Weight (kN/m^3)	c' (kPa)	ϕ' (degree)
Colluvium	19.6	10.0	35.0
Completely Weathered Granite	19.6	15.1	35.2
Completely to Highly Weathered Granite	19.6	23.5	41.5

Soil suctions were measured at this site using a tensiometer inserted through small openings made into the face of the slope. Figure 6 shows two typical suction profiles obtained from near section A-A. The suctions varied considerably since the measurements were influenced by the proximity of the slope face. Measurements on the upper part of the profile could not be accurately taken because the capacity of the tensiometer was exceeded.

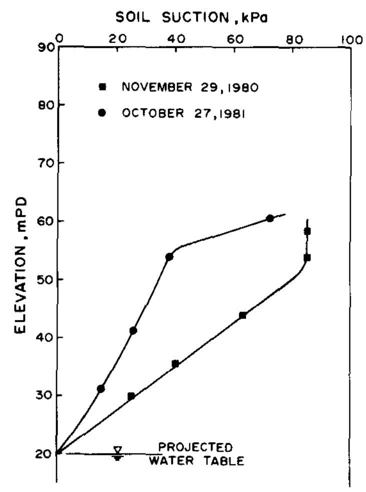

Fig. 6 Suction Measurements Obtained from Fung Fai Terrace

Stability Analysis at Fung Fai Terrace

Limit equilibrium stability analyses were performed on the three cross-sections shown in Figures 3, 4 and 5. The GLE method was used with the assumption that the resultant inter-slice forces are horizontal. Since numerical difficulties were often encountered in the analyses of steeply inclined slopes using a method involving the force equilibrium, a method satisfying only the moment equilibrium was used to solve for the factor of safety. The computations were performed using the SLOPE-II computer program (Fredlund, 1981). Circular surfaces were analyzed to determine the critical surface corresponding to a minimum factor of safety. All critical surfaces passed through the toe of the slope. Table II summarizes the stability results without the effect of soil suction.

TABLE II

Stability Results for Fung Fai Terrace without the Effect of Suction

Section	Center of Rotation* (m) X	Y	R	Factor of Safety
A-A	232.5	190.0	216.0	0.864
B-B	143.8	120.0	89.5	0.910
C-C	171.6	118.1	120.8	0.881

* Critical Center of Rotation

The most critical factor of safety is 0.86. The results indicate that the slope would be unstable if all conditions were representative. The fact that this slope has remained stable implies that the analysis is not completely representative of the field conditions. An additional strength is available, possibly due to soil suction.

The cross-sections were re-analyzed including the effect of soil suction. Each of the cross-sections was further divided into sub-strata drawn parallel to the water table in order to account for the varying suction. Sub-strata were 5 metres thick. Figure 7 shows the sub-division for cross-section A-A. Each of the sub-strata was assumed to have a different total cohesion, c, as described by equation (2). The equivalent increase in cohesion for a sub-stratum was interpreted from the respective matric suction profile.

A parametric study was conducted to demonstrate changes in the factor of safety in response to variations in the matric suction. Suction profiles as shown in Figure 1 were assumed. Results for the parametric study are summarized in Table III and plotted in Figure 8. Figure 8 shows that a suction profile of 10 to 20 percent negative hydrostatic pressure is required to render a factor of safety of 1. The factor of safety for various sections is increased by 10 to 40 percent for matric suction profiles corresponding to 10 to 100 percent of negative hydrostatic pressure, respectively. Figure 9 shows the variations in the position for the critical centre for section A-A. The critical slip surface tends to penetrate deeper into the slope as the cohesion increases.

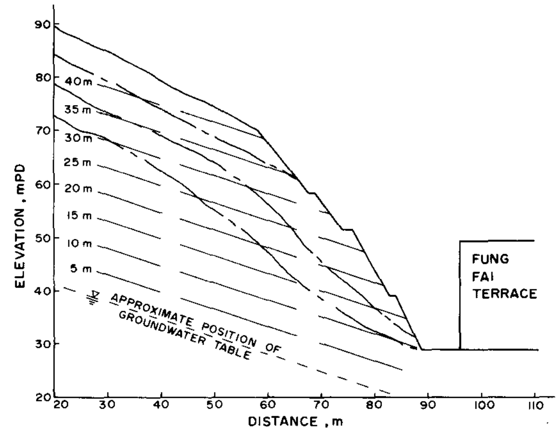

Fig. 7 Soil Subdivision for Section A-A of Fung Fai Terrace

TABLE III

Stability Results for Parametric Study for Fung Fai Terrace

A. Section A-A

Percent of Hydrostatic Suction	Center of Rotation (m) X	Y	R	Factor of Safety
10	210.0	175.0	190.0	0.948
20	200.0	167.0	178.0	1.030
30	185.0	150.0	155.0	1.108
50	180.0	150.0	151.0	1.179
100	173.3	139.0	139.0	1.226

B. Section B-B

Percent of Hydrostatic Suction	Center of Rotation (m) X	Y	R	Factor of Safety
10	130.6	112.5	78.8	1.011
20	130.6	112.5	78.8	1.097
30	133.1	117.5	81.4	1.184
50	130.0	117.5	79.8	1.274
100	143.8	132.5	99.7	1.308

C. Section C-C

Percent of Hydrostatic Suction	Center of Rotation (m) X	Y	R	Factor of Safety
10	151.3	102.5	95.7	0.991
20	138.8	96.3	83.1	1.088
30	134.1	93.1	77.8	1.179
50	138.8	96.3	83.1	1.267
100	138.8	96.3	83.1	1.296

Stability calculations were also performed using the actual matric suction values obtained from the field (Figure 6) to assess the actual stability of the slope. The average increase in cohesion for each soil sub-stratum was calculated from the actual matric suction profile up to the corresponding maximum value (Figure 6). The results are presented in Table IV. The overall factor of safety is approximately 1.10 based on the suction profile measured on November 29, 1980 whereas it is about 1.01 based on the suction profile measured on October 27, 1981.

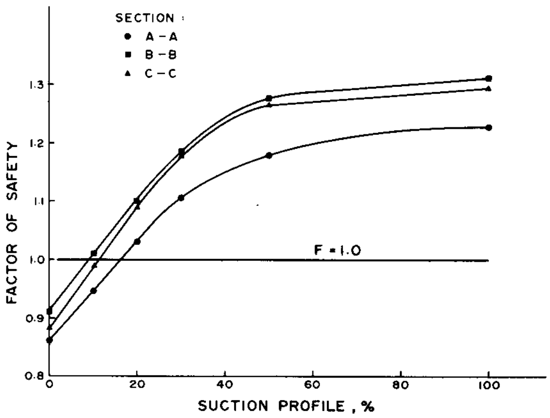

Fig. 8 Results of Parametric Stability Analysis for Fung Fai Terrace

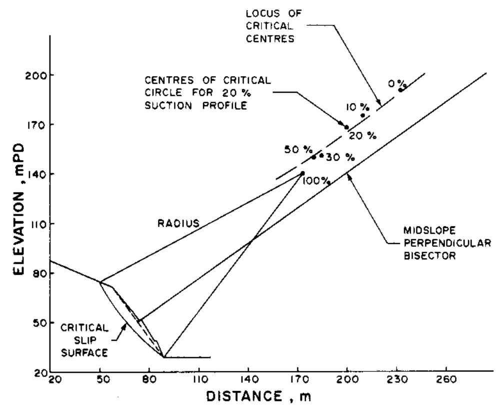

Fig. 9 Critical Centres for Section A-A

TABLE IV

Stability Results with the Effect of Suction for Fung Fai Terrace

A. Suction Profile (November 29, 1980)

Section	Center of Rotation (m) X	Y	R	Factor of Safety
A-A	176.3	141.9	143.0	1.072
B-B	133.1	117.5	81.4	1.143
C-C	138.8	96.3	83.1	1.132

B. Suction Profile (October 27, 1981)

Section	Center of Rotation (m) X	Y	R	Factor of Safety
A-A	201.3	167.5	178.6	0.984
B-B	165.0	125.0	122.2	1.046
C-C	156.9	108.8	104.1	1.014

Study Site 2: Thorpe Manor

Thorpe Manor is a site located in the Mid Levels district of Hong Kong Island. It has been proposed for a high-rise residential building. An unusually steep and high cut slope exists below the site, accommodating an existing residential building. This led to a detailed investigation to access the long-term stability of the site taking into account of the imposed loads from the new building and induced changes in surface and subsurface drainage.

Figure 10 shows the site plan of Thorpe Manor, which is topographically situated at the front of a spur protruding from the main hillside. The cut slope under consideration is below a major access road (i.e., May Road) and its critical cross-section, A-A, is shown in Figure 11. The slope is inclined at 60 degrees to the horizontal and has an average height of 30 metres. The stratification consists entirely of weathered rhyolite. The surficial material is a completely weathered rhyolite of 5 to 10 metres in thickness. The second stratum is a layer of completely to highly weathered rhyolite varying from 5 to 10 metres in thickness. Underlying is another layer of slightly weathered rhyolite. Bedrock is located approximately 20 to 30 metres below the surface. The water table lies well below the ground surface. It is estimated that the water table will rise less than 5 to 8 metres under the influence of heavy rain with return periods of 10 and 1000 years, respectively. Therefore, the water table does not directly influence the stability analysis.

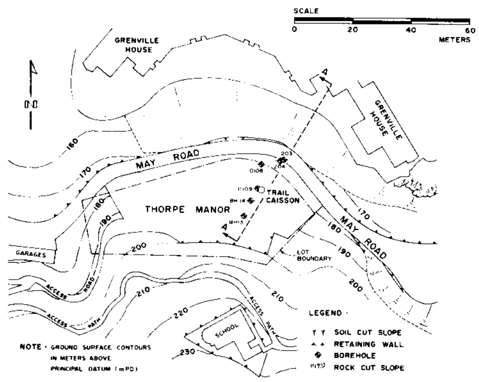

Fig. 10 Site Plan of Thorpe Manor

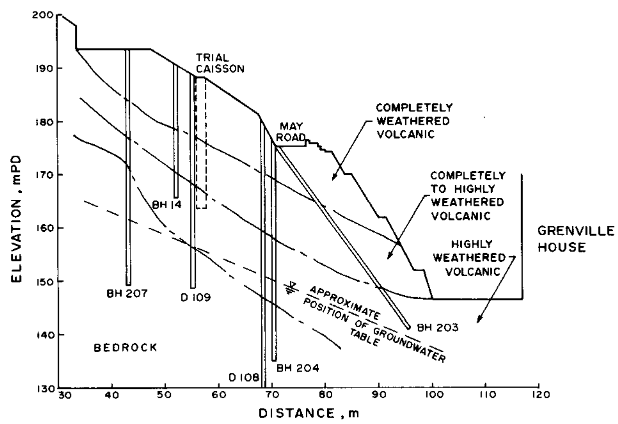

Fig. 11 Section A-A of Thorpe Manor

TABLE V

Properties for Soils at Thorpe Manor

Soil Type	Unit Weight (kN/m^3)	c' (kPa)	ϕ' (degree)	ϕ^b (degree)
Completely Weathered Rhyolite	18.4	10.1	42.6	12.0
Completely to Highly Weathered Rhyolite	21.4	12.0	43.9	12.0

Undisturbed core samples were tested to obtain the shear strength parameters. The ϕ^b angle for the soils was independently evaluated. Table V gives a summary for the soil properties.

Insitu soil suction measurements were made from an exploratory caisson shaft installed near the cut slope (Figure 10). Suction profiles obtained during the rainy season of 1980 are plotted in Figure 12. These profiles are relatively uniform, except that variations occurred as a result of infiltration and fluctuation in the position of the water table.

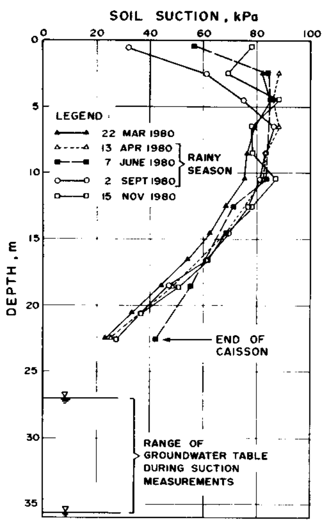

Fig. 12 Suction Measurements Obtained from Thorpe Manor

Stability Analysis for Thorpe Manor

Stability analyses using circular slip surfaces were performed on section A-A. The computations were first made assuming saturated conditions. A parametric study was included in order to evaluate the effect of the changes in the soil suction profile and the water table on the computed factor of safety. Various suction profiles were assumed. Water tables corresponding to heavy rains with return periods of 10 and 1000 years, respectively, were used. Results for the stability analyses are summarized in Table VI.

The critical factor of safety for the cut slope without the effect of soil suction is approximately 1.05, suggesting that this slope is in a nearly unstable condition although no distress is observed. Its value is increased to 1.25 when including the actual soil suctions. In other words, matric suction contributes approximately 20% towards an increased factor of safety.

Results from the parametric study show that factor of safety computations are sensitive to changes in the suction profile but less sensitive to the position of the water table. The computed factor of safety is 1.43 when using a matric suction profile equivalent to 100 percent of negative hydrostatic pressure. For water table positions corresponding to heavy rains with return periods of 10 and 1000 years, the respective factors of safety are 1.37 and 1.32.

TABLE VI

Stability Results for Thorpe Manor

A. Approximate Water Table

Suction Profile (%)	Center of Rotation (m) X	Y	R	Factor of Safety
0	148.8	205.0	76.1	1.046
10	141.3	202.5	69.6	1.114
20	139.7	202.5	68.6	1.181
30	138.1	202.5	67.7	1.242
50	135.0	202.5	66.0	1.342
100	135.0	202.5	66.0	1.428
Actual*	126.9	192.5	53.3	1.254

* Suction profile of September 2, 1980

B. Water Table Corresponding to 1:10 Year Rain

Suction Profile (%)	Center of Rotation (m) X	Y	R	Factor of Safety
10	145.0	205.0	73.8	1.091
20	141.3	202.5	69.6	1.139
30	150.0	212.5	82.8	1.191
50	141.9	207.5	74.0	1.270
100	136.9	202.5	67.1	1.370

C. Water Table Corresponding to 1:1000 Year Rain

Suction Profile (%)	Centre of Rotation (m) X	Y	R	Factor of Safety
10	145.0	205.0	73.8	1.078
20	141.3	202.5	69.6	1.114
30	160.0	220.0	94.9	1.159
50	141.9	207.5	74.0	1.216
100	148.1	212.5	81.7	1.320

DISCUSSION

The increase in soil strength due to matric suction is generally ignored in the stability analysis of slopes. This is mainly because of the uncertainties regarding the long term reliability of the soil suctions. In general, it has been assumed that there will be a complete loss of soil suction due to an ingress of water. This conventional approach, in many cases, will give conservative factors of safety. Analyses using this approach for the Hong Kong residual soil slopes underestimate the actual factor of safety and may detract from using wise engineering judgments in designs. It is postulated that long term soil suction profiles play a significant role in the stability of many steep natural and cut slopes.

Stability studies on the two cut slopes in Hong Kong provide valuable case histories on the quantification of the influence of soil suction on stability. The computed factors of safety appear to be unrealistically low when saturated conditions are assumed. When the effect of soil suction is included, the stability results become more reasonable in the sense that they better represent the actual observed stability conditions.

The computed factors of safety for the cut slopes at Fung Fai Terrace and Thorpe Manor are approximately 0.86 and 1.05, respectively, when neglecting the effect of soil suction. The factors of safety are increased to 1.01 and 1.25 when taking into consideration the actual soil suctions. It is concluded that the soil suction does make a substantial contribution to the stability for the two slopes.

Suctions may vary with time. However, measurements have indicated that significant soil suctions in the two slopes are maintained throughout the wet and dry seasons. In both cases, the soil in the cut slopes is protected from infiltration by chunam plaster while infiltration above the chunam cover is inhibited by the steepness of the ground and thick vegetation.

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