Slope Stability
Edited by M. G. Anderson and K. S. Richards

Chapter 4

Slope Stability Analysis Incorporating the Effect of Soil Suction

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4.1 INTRODUCTION

Slope stability analyses have become a common analytical tool to assess the factor of safety of natural and man-made slopes. Saturated shear strength parameters are generally used in the analysis. The portion of the soil profile above the groundwater table where the pore-water pressures are negative is usually ignored. This is a reasonable assumption for many situations where the major portion of the slip surface passes through saturated soil. However, for situations where the groundwater table is deep or where the concern is over the possibility of a shallow failure, there is need to understand how to perform slope stability analyses where the soil is unsaturated. The main objective of this paper is to discuss the developments in slope stability analysis to incorporate the effect on strength of suction in the unsaturated zone.

In order to maintain an analytical procedure for unsaturated soil mechanics, several aspects must be addressed (Fredlund, 1979). First, it must be possible to measure appropriate shear strength parameters for the unsaturated soils. Preferably these should provide a smooth transition to the saturated shear strength parameters. Second, techniques must be available to measure or estimate the *in situ* negative pore-water pressure conditions. If an assessment of the factor of safety is required for a particular instant in the history of the slope, it is possible either to measure the suction *in situ* or on laboratory samples. The problem becomes more demanding when it is necessary to predict possible changes in the soil suction profile throughout the seasons. Third, the conventional, limit equilibrium, slope stability analysis must be extended to incorporate the shear strength equation for unsaturated soils. Once verified through a series of case histories, the method of slope stability analysis for unsaturated soils becomes an extention of the procedure used for saturated soils.

where: $f(x)$ = a functional relationship which describes the manner in which the magnitude of X/E varies across the slip surface.
λ = a scaling constant which represents the percentage of the function, $f(x)$, used for solving the factor of safety equations.

Until recently, the $f(x)$ was arbitrarily selected. Wilson and Fredlund (1983) and Fan (1983) performed finite element analyses on slopes of varying inclinations and studied a wide variety of possible slip surfaces. The results yielded an empirical interslice force function of the form:

where: e = base of the natural logarithm.
K = magnitude of the interslice force function at midslope (i.e. maximum value).
C = variable to define the inflection points.
n = variable to specify the flatness or sharpness of curvature.
ω = dimensionless x-position relative to the midpoint of the slope.

The variable, K, is a function of the slope inclination and the depth factor. The constants 'C' and 'n' are related to the slope inclination. A summary of the magnitudes of all constants is presented by Fredlund (1984).

The above slope stability analysis can be simplified if desired, by (a) electing to consider only circular slip surfaces; (b) electing to satisfy only the moment or the force equilibrium factor of safety equation; or (c) assuming the interslice shear forces are negligible.

4.4 APPLICATIONS OF SLOPE STABILITY ANALYSIS

The increase in the factor of safety due to negative pore-water pressures (or matric suction) can readily be demonstrated by studying the influence of increasing the cohesion. Particularly on shallow slip surfaces, the cohesion component significantly affects the computed factor of safety. Fredlund (1981a) selected a typical cross-section and soil properties for a slope in Hong Kong (Figure 4.18) and demonstrated the effect of increasing the cohesion on a selected slip surface (Figure 4.19). The factor of safety increased two-fold for an increase in cohesion of 60 kPa. Conversely, it can readily be appreciated that the factor of safety of a slope can decrease significantly when the cohesion due to matric suction is decreased during a prolonged wet period.

The additional factors which require engineering judgement when performing slope stability analyses on unsaturated soil slopes, are the assessment of ϕ^b and the matric suction profile. Test results to date indicate that the ϕ^b angle is always less than ϕ'. Typical values for ϕ^b range from 13 to 20 degrees.

The assessment of the relevant negative pore-water (or matric suction) profile is difficult and depends upon the problem being addressed. Typical situations can be outlined as follows:

1. There may be interest in performing a back-analysis on a slope which has just failed. Measurements of actual negative pore-water pressures just prior to failure or just

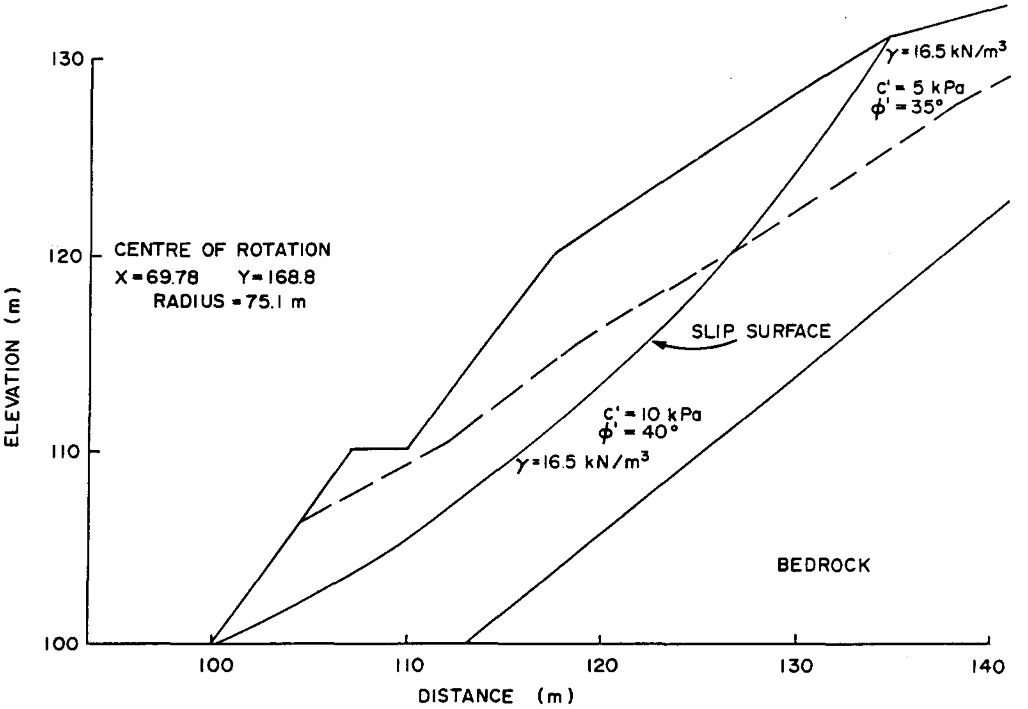

Figure 4.18 Example of a typical slope in Hong Kong (the material properties relate to two zones in granitic colluvium above the bedrock)

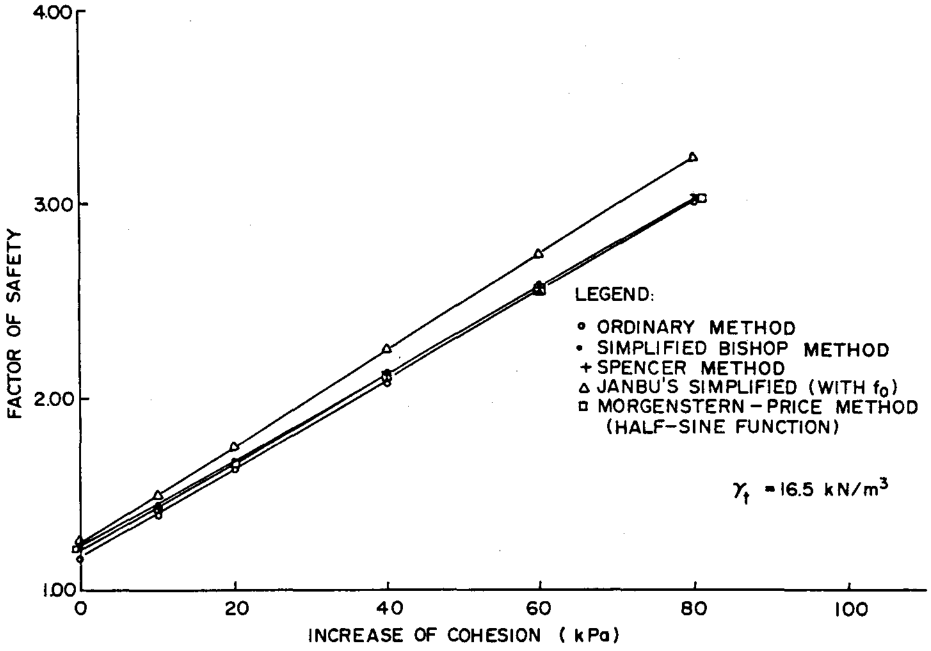

Figure 4.19 Increase in factor of safety for an increase in cohesion for the example slope

following the failure would be most relevant for analytical purposes (Fontura *et al.*, 1984).

2. When assessing the short-term stability of a cut slope, an ongoing monitoring of the negative pore-water pressures should provide the most valuable input into the analysis. The computed factor of safety must be maintained well in excess of 1.0 to ensure stability.
3. In the case of the assessment of the stability of natural or man-made slopes, the negative pore-water pressure profile to be used in an analysis is more difficult to ascertain (Lumb, 1975). Most natural soil deposits are desiccated near ground surface and contain cracks and fissures forming a secondary soil structure of varying depths. This provides easy access of water to the soil and can play a major role in rapidly decreasing the matric suction during periods of prolonged rainfall. Some soil deposits, although intact, may be highly porous and allow a rapid reduction in matric suction during rainy periods.

Other soil deposits are relatively intact and appear to maintain their negative pore-water profiles even during prolonged rainy periods (Sweeney, 1982). In these situations, the engineer must select the lower limit of the pore-water pressure profile for design purposes. In some situations this may be an unwise solution to the problem whereas in other situations it may be the only realistic solution (Widger and Fredlund, 1979). Certainly there is need for more detailed case histories in order to ensure a higher level of confidence in design.

In the early 1980s two sites were selected in Hong Kong where the relevant variables would be measured to study the influence of matric suction on the factor of safety (Sweeney and Robertson, 1979). The two sites were Fung Fai Terrace and Thorpe Manor (Ching *et al.*, 1984). In each case the soil stratigraphy was determined from numerous borings. Undisturbed soil samples were used to measure the shear strength parameters in the laboratory. Negative pore-water pressures were measured *in situ*. Stability analyses were then performed to assess the effect of soil suction. Parametric type analyses were also performed using varying percentages of the negative hydrostatic condition in the analysis. The negative pore-water pressures were converted to equivalent cohesion values using a ϕ^b angle of 15° (Figure 4.20).

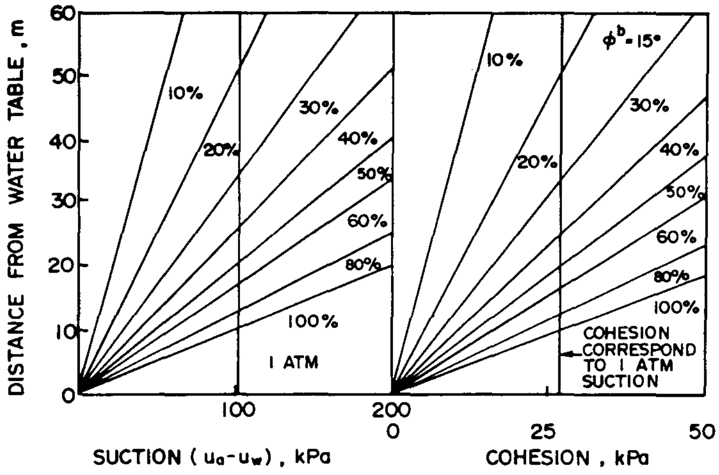

Figure 4.20 Equivalent increase in cohesion for various soil suction profiles

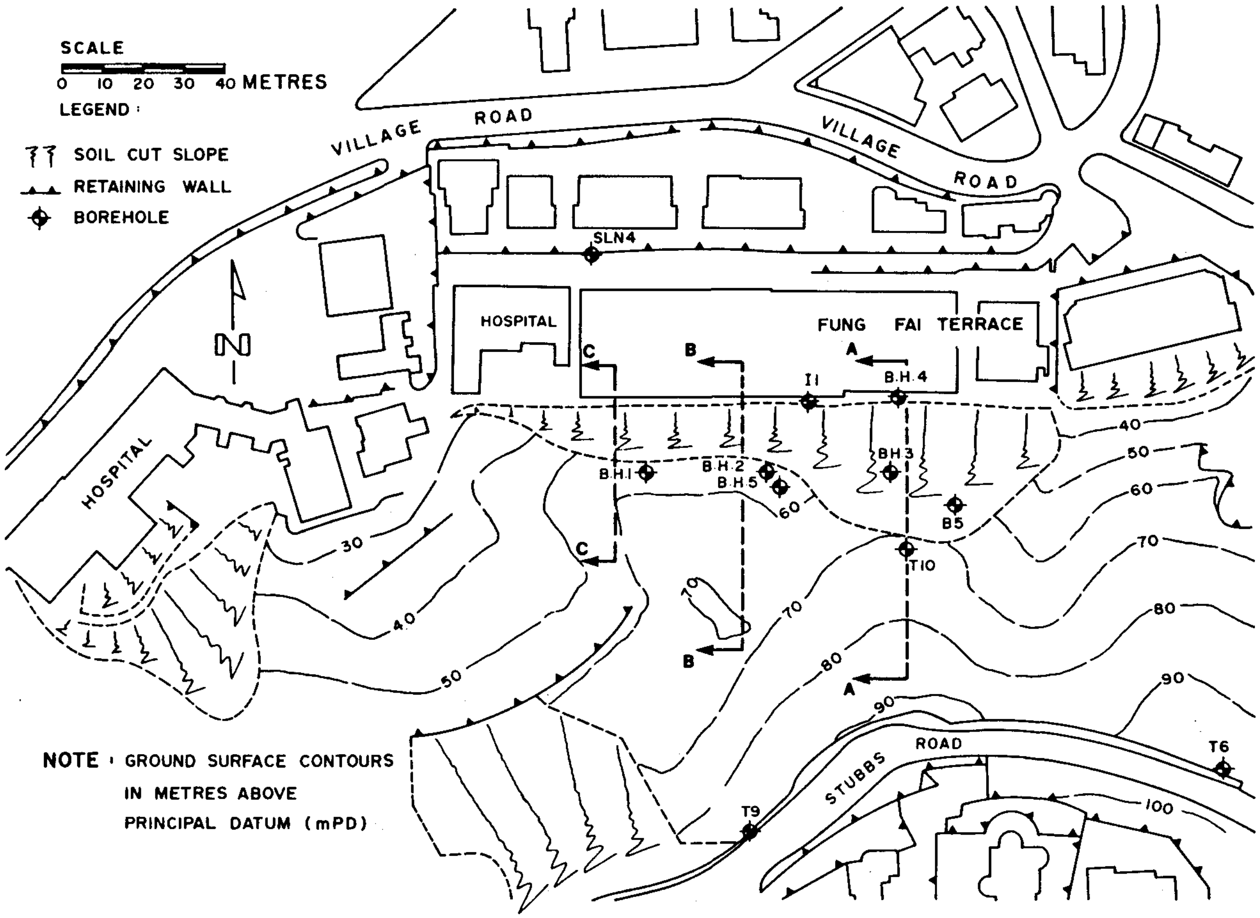

Figure 4.21 Site plan for Fung Fai Terrace, Hong Kong

4.4.1 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 4.21. 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; see Chapter 7) 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.

Three cross-sections A–A, B–B and C–C are shown in Figures 4.22 to 4.24. The stratigraphy consists primarily of weathered granite. There is a layer of granitic colluvium, 4 to 5 metres thick, present at the top of the slope. Beneath the colluvium is a layer of completely to highly weathered granite of about 10 metres thickness. 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 1,000 years, respectively. The groundwater level does not directly affect the stability analyses.

Undisturbed core samples were tested to establish the pertinent strength parameters. Results are given in Table 4.5. The average ϕ^b angle for the soils was taken as 15 degrees (Ho and Fredlund, 1982b).

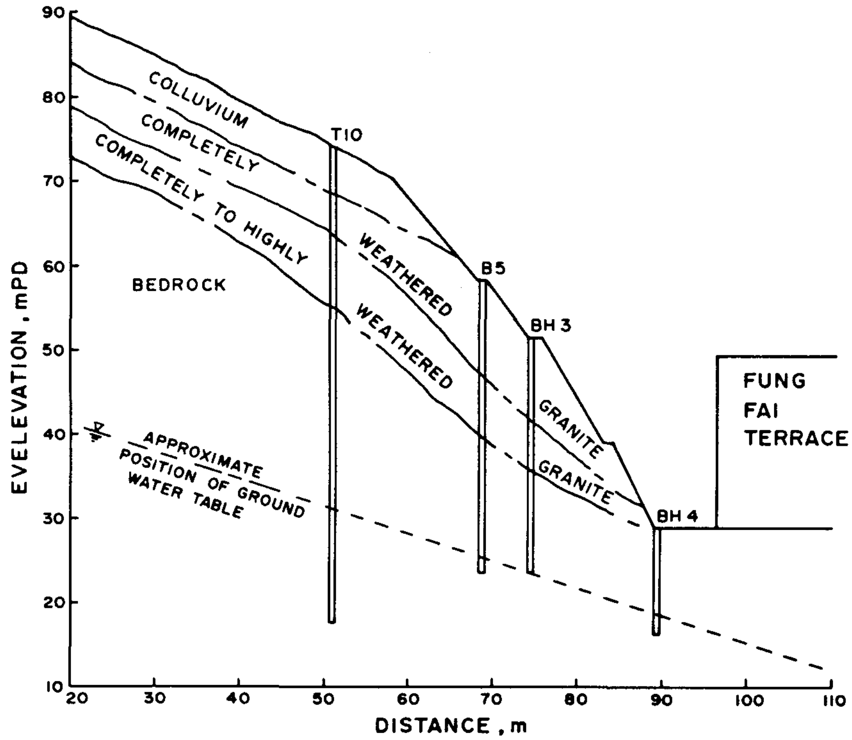

Figure 4.22 Section A–A for Fung Fai Terrace, Hong Kong

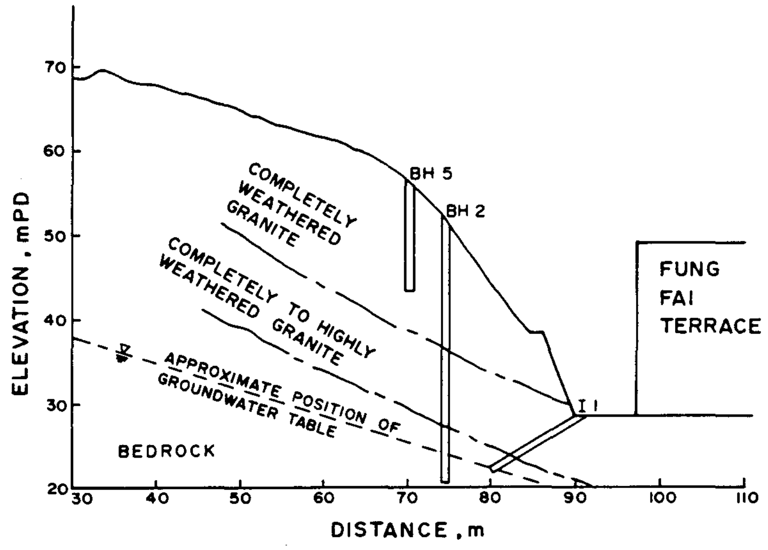

Figure 4.23 Section B-B for Fung Fai Terrace

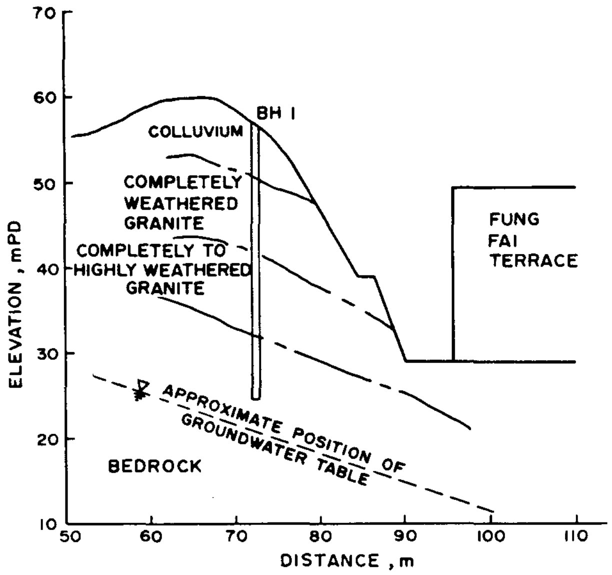

Figure 4.24 Section C-C for Fung Fai Terrace

Table 4.5 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

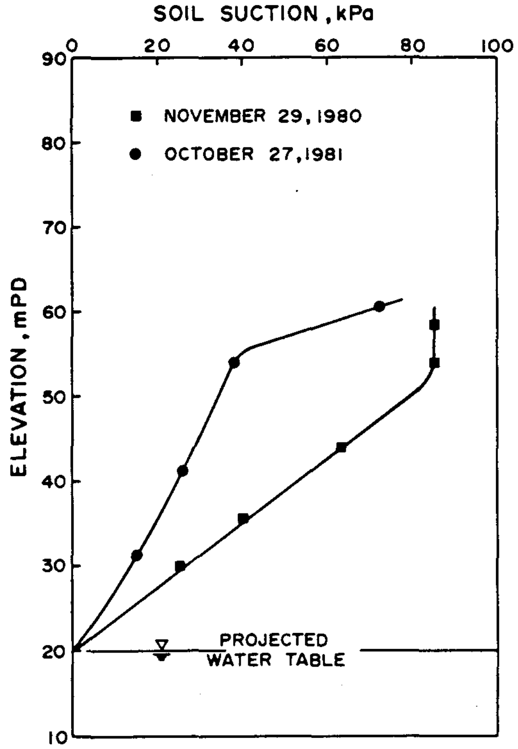

Figure 4.25 Suction measurements at Fung Fai Terrace

Soil suctions were measured at this site using a tensiometer inserted through small openings made into the face of the slope. Figure 4.25 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. Suctions on the upper part of the profile could not be accurately measured because the capacity of the tensiometer was exceeded.

4.4.1.1 Stability Analysis at Fung Fai Terrace

Limit equilibrium stability analyses were performed on the three cross-sections shown in Figures 4.22 to 4.24. The assumption was made that the resultant interslice forces were horizontal. The computations were performed using the SLOPE-II computer program (Fredlund, 1981b). Circular surfaces were analysed to determine factor of safety. All critical surfaces passed through the toe of the slope. Table 4.6 summarizes the stability results without the effect of soil suction.

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.

Table 4.6 Stability Results for Fung Fai Terrace without the Effect of Suction

Section	Centre of Rotation* (metres) X-Coordinate	Y-Coordinate	Radius	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 centre of rotation.

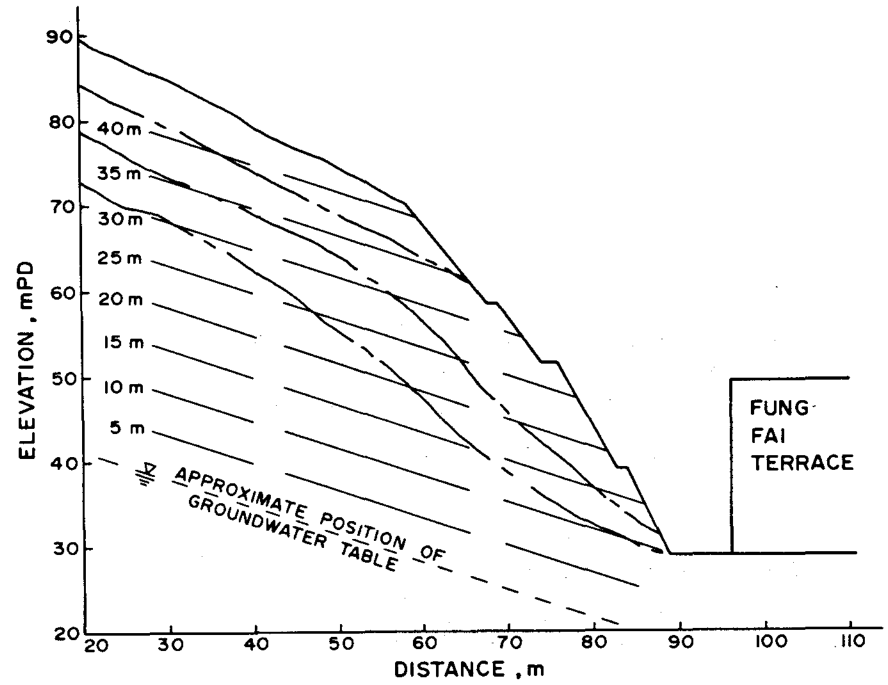

Figure 4.26 Subdivision of section A–A at Fung Fai Terrace for slope stability analysis

The cross-sections were re-analysed 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 matric suction. Each sub-stratum was 5 metres thick. Figure 4.26 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 (4.2).

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 4.20 were assumed. Results for the parametric study are summarized in Table 4.7 and plotted in Figure 4.27. Figure 4.27 shows that a suction profile of 10 to 20% 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% for matric suction profiles corresponding to 10 to 100% of negative

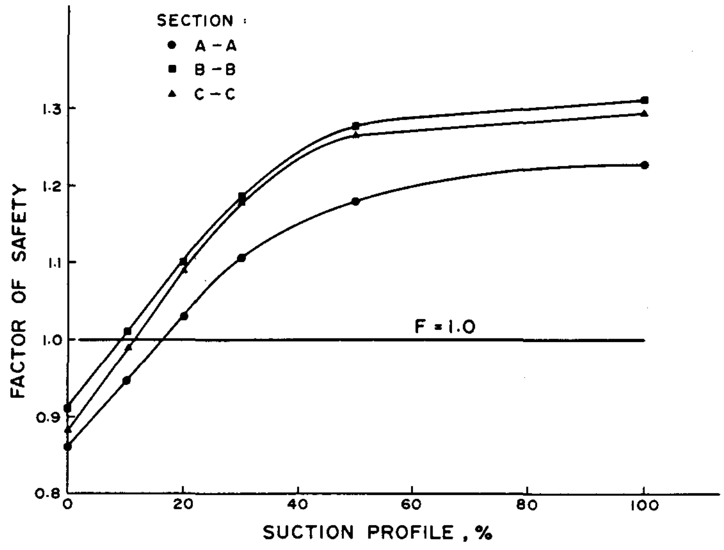

Figure 4.27 Results of a parametric slope stability study for Fung Fai Terrace

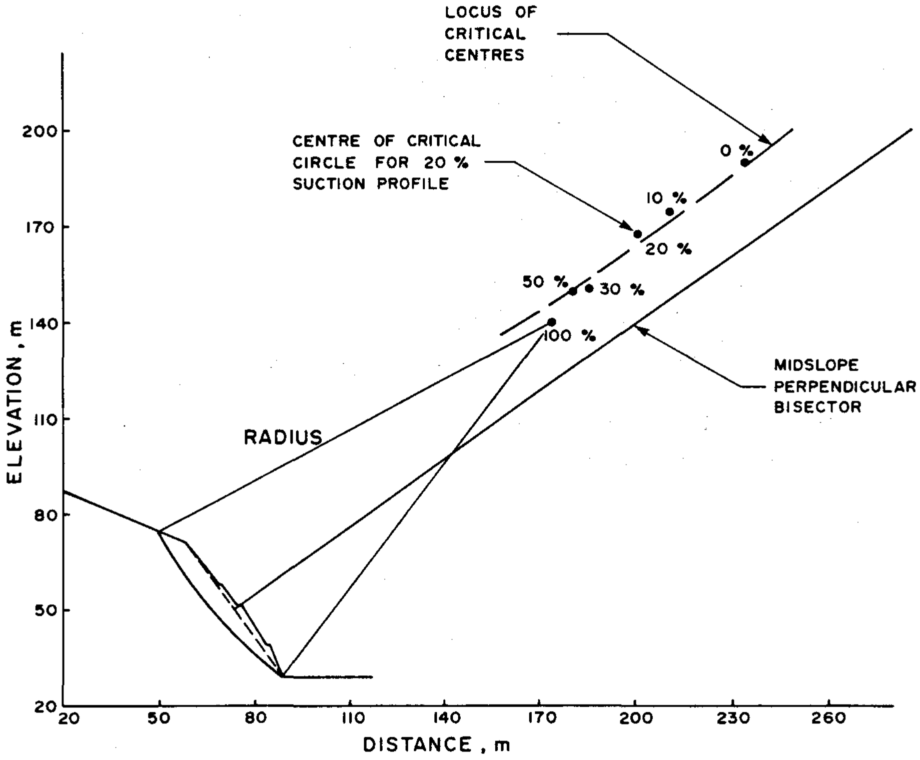

Figure 4.28 Critical centres for various suction profiles on section A–A

Table 4.7 Stability Results for Parametric Study for Fung Fai Terrace

A. Section A–A

Per cent of hydrostatic condtions	Centre of Rotation (m) X-Coordinate	 Y-Coordinate	Radius	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

Per cent of hydrostatic conditions	Centre of Rotation (metres) X-Coordinate	 Y-Coordinate	Radius	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

Per cent of hydrostatic conditions	Centre of Rotation (metres) X-Coordinate	 Y-Coordinate	Radius	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

hydrostatic pressure, respectively. Figure 4.28 shows the variation in the position of the critical centre for section A–A. The critical slip surface tends to penetrate deeper into the slope as the cohesion increases.

Stability calculations were also performed using the actual matric suction values obtained from the field (Figure 4.25). The average increase in cohesion for each soil sub-stratum was calculated from the actual matric suction profile up to a maximum suction value of one atmosphere (Figure 4.25). The results are presented in Table 4.8. The overall factor of safety is approximately 1.10 based on the suction profile measured on 29 November 1980 whereas it is about 1.01 based on the suction profile measured on 27 October 1981.

4.4.2 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

Table 4.8 Stability Results with the Effect of Suction for Fung Fai Terrace

A. Suction Profile (29 November 1980)

	Centre of Rotation (metres)			Factor of Safety
Section	*X*-Coordinate	*Y*-Coordinate	Radius	
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 (27 October 1981)

	Centre of Rotation (metres)			Factor of Safety
Section	*X*-Coordinate	*Y*-Coordinate	Radius	
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

investigation to access the long-term stability of the site taking into account the imposed loads from the new building and induced changes in surface and subsurface drainage.

Figure 4.29 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 and its critical cross-section, A–A, is shown in Figure 4.30. The slope is inclined at 60 degrees to the horizontal and has an average height of 30 metres. The stratigraphy 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 1,000 years, respectively. Therefore, the water table does not directly influence the stability analysis.

Undisturbed core samples were tested to obtain the saturated shear strength parameters. The ϕ^b angle for the soils was independently evaluated. Table 4.9 gives a summary for the soil properties. *In situ* soil suction measurements were made from an exploratory caisson shaft installed near the cut slope (Figure 4.29). Suction profiles obtained during the rainy season of 1980 are plotted in Figure 4.31. These profiles are relatively uniform, except for variations which occurred as a result of infiltration and fluctuation in the position of the water table.

4.4.2.1 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

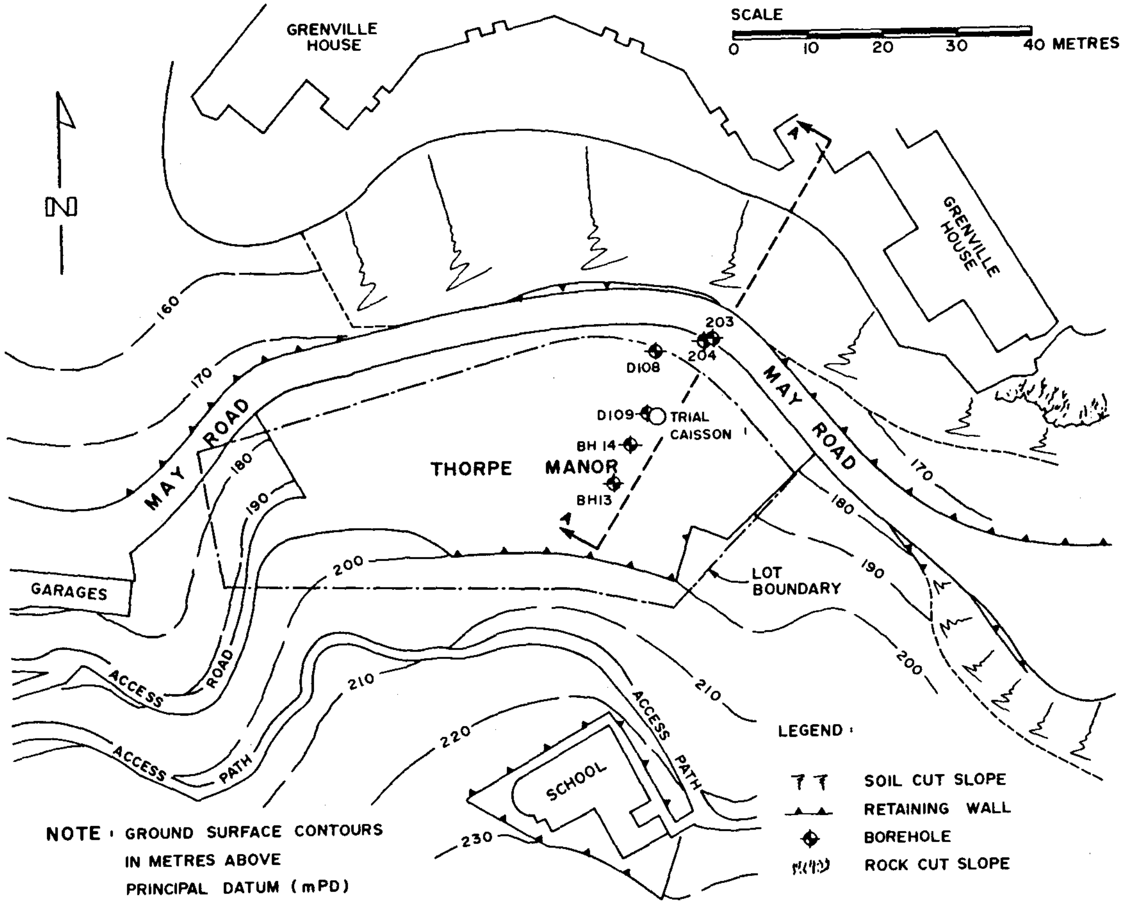

Figure 4.29 Site plan for Thorpe Manor, Hong Kong

Table 4.9 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

Table 4.10 Stability Results for Thorpe Manor

A. Approximate Water Table

Suction Profile (%)	Centre of Rotation (metres) X-Coordinate	Y-Coordinate	Radius	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 2 September 1980

B. Water Table Corresponding to 1:10 Year Rain

Suction Profile (%)	Centre of Rotation (metres) X-Coordinate	Y-Coordinate	Radius	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 1:1,000 Year Rain

Suction Profile (%)	Centre of Rotation (metres) X-Coordinate	Y-Coordinate	Radius	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

assumed. Water tables corresponding to heavy rains with return periods of 10 and 1,000 years, respectively, were used. Results from the stability analyses are summarized in Table 4.10.

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

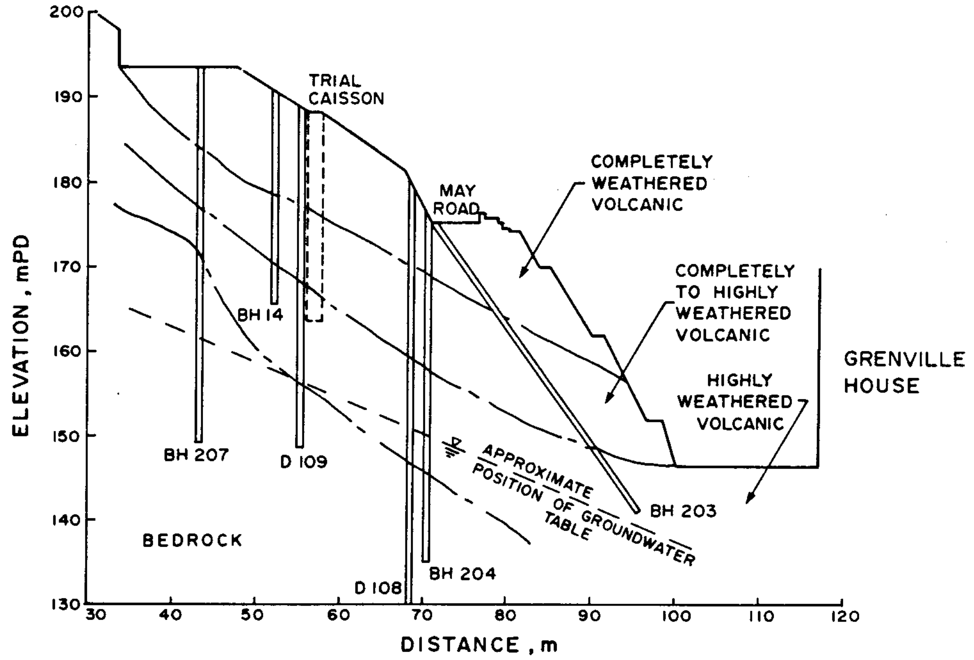

Figure 4.30 Section A-A for Thorpe Manor, Hong Kong

no distress is observed. Its computed factor of safety 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 critical factor of safety is 1.43 when using a matric suction profile equivalent to 100% of negative hydrostatic pressure.

4.5 CONCLUSIONS

During the past few years, a much clearer appreciation has emerged regarding the influence of soil suction on the stability of slopes. The shear strength equation for unsaturated soils has gained wide acceptance, and testing procedures have been proposed for measuring the shear strength parameters for unsaturated soils. The new strength parameter required is the angle, ϕ^b. This angle appears to be commonly of the order of 15 degrees; however, further testing and research are required for a better understanding of this soil parameter. The theoretical formulations for conventional limit equilibrium methods of slices have been extended to embrace unsaturated soils. These equations can readily be solved using computers. The greatest need relates to the measurement of *in situ* negative pore-water pressures. More studies are needed of the changes in pore-water pressure from season to season and further case studies are needed of

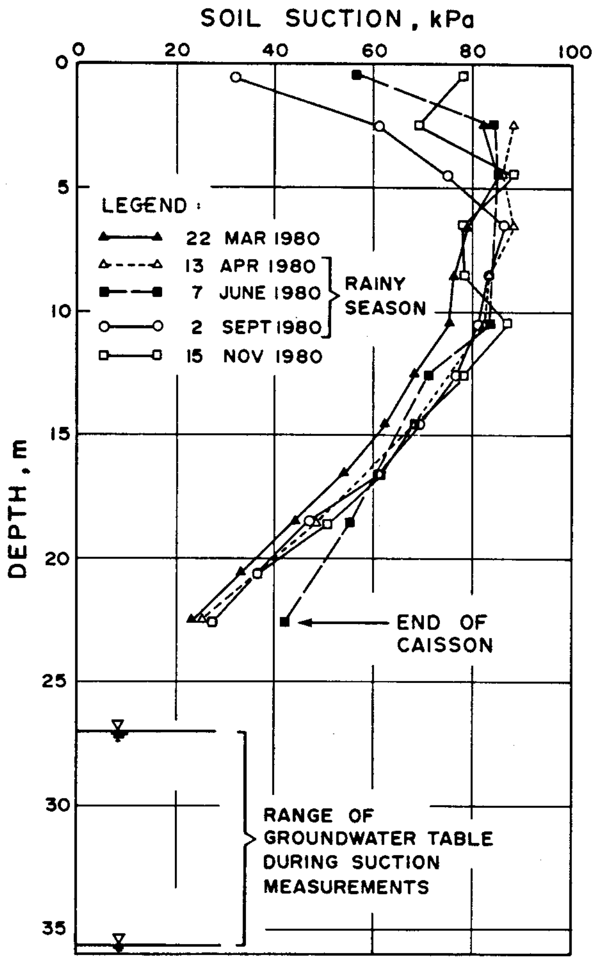

Figure 4.31 Soil suction measurements at Thorpe Manor

stability problems in unsaturated soils to promote confidence in the analysis outlined in this chapter.

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