Soil Suction in Relation to Slope Stability: A Summary of Research Carried Out in Hong Kong in 1978-1997

J. M. Shen

Geotechnical Engineering Office, Civil Engineering Department, Hong Kong

Abstract: The research carried out in Hong Kong on soil suction in relation to slope stability in the years 1978-1997, mostly initiated by the Geotechnical Engineering Office (the abbreviation GEO will be used throughout this paper, though it was called GCO before 1991), is briefly described in this paper with the author's comments. The research described falls broadly into three areas: field measurement of suction; model for predicting change in suction; and effect of suction on shear strength of a soil. It is hope that this historical account could inform readers of the vast amount of work that has been carried out in this area, and reactivate interest in the subject.

1 INTRODUCTION

When the steep man-made slopes in Hong Kong are analysed using saturated shear strength parameters it is often found that the factor of safety is less than one. Suction is thought to provide the main explanation as the slopes may not become fully saturated even during severe rainstorms although it may be prudent to make such assumptions for the design of slopes. To confirm this hypothesis, and to investigate the possibility of incorporating suction into slope design, answers to two questions are required, viz

(1) how much suction could we rely upon to exist in the slope during/after the design extreme storm and
(2) how does suction affect the shear strength of the soil.

Since the early days of the GEO much research work has been carried out, by GEO and others, on the effect of soil suction on slope stability in Hong Kong. The research work falls into three main areas as follows, the first two areas being related to question (1) and the third related to question (2):

(a) field measurement of suction;
(b) establishment of a model for understanding and predicting change of suction; and
(c) quantification of effect of suction on shear strength.

Research work carried out in these three areas are briefly described in this paper and suggestions were made for future development.

2 PRE-GEO RESEARCH

Suction has attracted local attention before the days of the GEO and main work include Wong (1970) related to the measurement of suction by the psychrometer and Lumb (1962) and Wong (1966) on the propagation of the wetting front during rainstorm. The latter work, however, was formulated in terms of degree of saturation rather than suction and formed the basis of the "wetting band" theory for predicting the rise in water table in a rainstorm of a given return period, which is still being used today in design.

3 FIELD MEASUREMENTS OF SUCTION

Initially GEO started to look into various possible measuring devices such as the psychrometer (Gray & McFarlane 1979), the tensiometer and the hydraulic piezometer. After some trials using block samples in the laboratory it was soon realised the tensiometer is the most appropriate device due to its rapid response and the range of suction that is normally encountered locally. The tensiometer is a well proven and reliable product for agricultural use, for monitoring the moisture conditions in the soil to prevent corps from whitering.

According to McFarlane (1979), the first two tensiometers in Hong Kong were installed in May 1979 at the HKU in a granitic soil on a level site to depths of 0.8 and 1.0 m and monitored for two months, measuring suctions between 0 and 28 kPa, with suctions reducing after heavy rainfall and increasing during prolonged dry periods. This was followed by trial installations in the Mid-levels and Chai Wan, which were removed after a few hours when suction readings stabilised. This is then followed by a group of 12 tensiometers and four hydraulic piezometers into the slope at the rear of Charter Hall Flats in Conduit Road as part of the Mid-levels study (GCO 1982).

McFarlane (1980) reported subsequent installations at five locations at King's Park, Lung Cheung Road, Hong Kong Sanitorium (Happy Valley), Kennedy Town Service Reservoir and Po Shan Road. These normally consisted of groups of tensiometers up to 3 m depth, both under vegetated and chunam cover. These

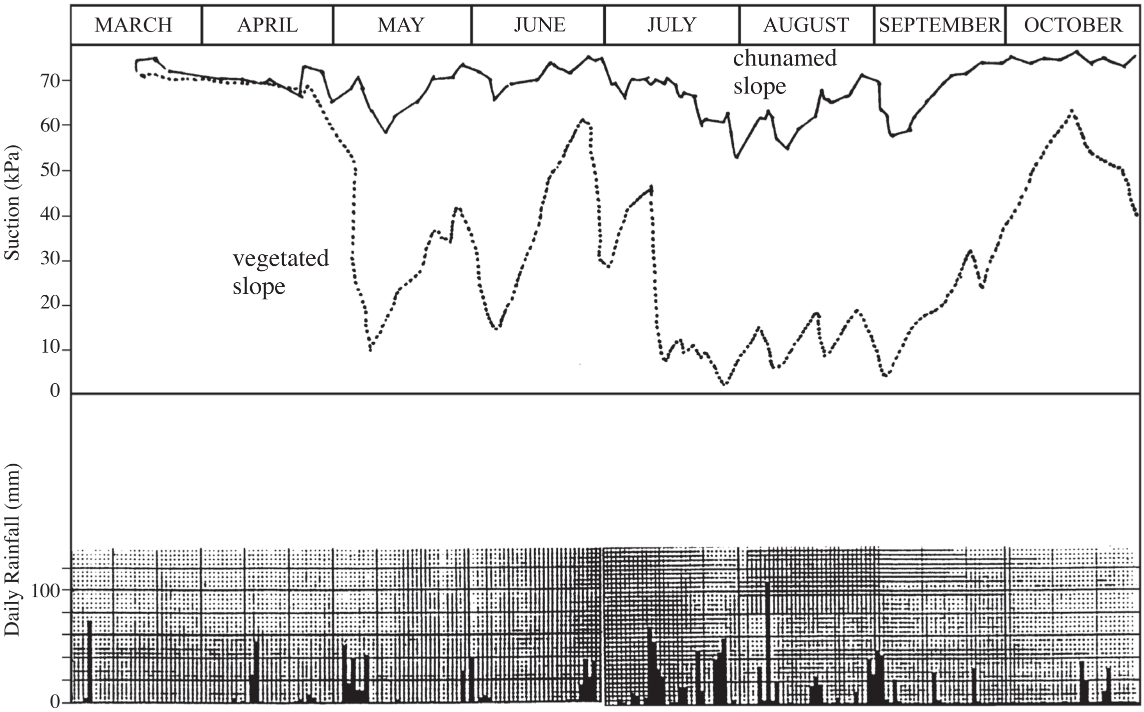

Figure 1. Measurement of suction at 1 m below surface for a slope in Lung Cheung Road in 1980, after McFarlane (1981 b)

installation were monitored weekly for a period of 2 years and the results were reported in McFarlane (1981 b), with a typical plot reproduced in Figure 1. Similar data were reported for a total of 47 tensiometers.

There were other field measurements initiated outside GCO. Anderson et al (1983) reported on the installation at St Christopher bend in Tai Po and Sweeney (1982) reported on measurements inside a caisson, which enabled the suction at great soil depth to be measured. There were also suction measurements in chunam covered fill slopes at So Uk Housing Estate and Pak Tin Housing Estate.

However, by far the most comprehensive measurement of suction in slopes was carried out on two adjacent slopes in Clear Water Bay Road, one chunamed, and the other grassed. A total of 30 tensiometers were installed on each slope and the suction was monitored for two years in 1982 - 83 with some results reported in Anderson (1984). A typical plot of suction contours in the chunamed slope are shown in Figure 2.

After the major field study at Clear Water Bay Road there was a period without significant attempt to measure suction in the field. However, recently field measurements of suction were carried out as part of forensic investigation of landslides, and suction measurement in a cut slope protected with no fine concrete was resumed at the Kennedy Town service reservoir site.

The results of all these measurements revealed a wide range of suction response during rainfall, from evidence of perched water table leading to positive pore pressure to the ability to maintain a high suction, e.g., the chunamed slope at Lung Cheung Road maintained a minimum suction of 50 kPa at 1 - 3 m depth during 1980.

Although the tensiometer was found to be the most appropriate for measurement of suction locally one draw back is that it required manual reading and de-airing. An early attempt to achieve automatic recording using scanning valve did not prove successful. Since pressure transducers were expensive in those days, the design was to have one pressure transducer to measure the suction of a group of tensiometers through a system of valves scanning in rotation. However, to avoid air entering the system the connection has to be made at a datum where the pressure is positive, as for the hydraulic piezometer. Also the problem of time of equilibrium is also difficult to solve. The cost of pressure transducers has since dropped significantly and it is now more affordable to have one transducer per tensiometer. Moreover, the recent development at Imperial College using a tensiometer probe of very small volume not only rendered manual de-airing unnecessary, but also appears to extend the range of measurable suction far in excess of the 100 kPa limit for the ordinary tensiometers. Its use with coarse grain soils had not been tried but it should have good potential for use in Hong Kong.

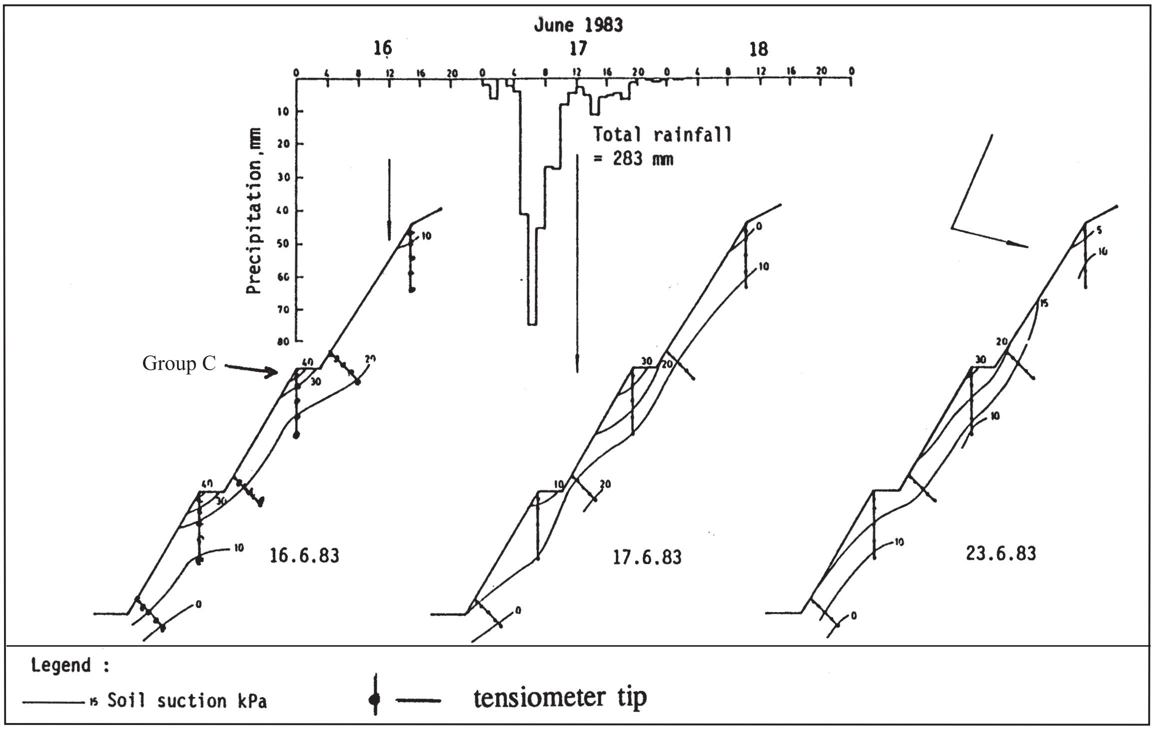

Figure 2. Soil suction distributions of a chunamed slope in Clear Water Bay Road affected by a rainstorm on 17 June 1983, after Figure 4.14 of Anderson (1984)

4 PREDICTION OF CHANGE IN SUCTION

The early work of Lumb (1962) provided some understanding of the mechanism of wetting front and the importance of initial saturation (hence antecedent rainfall) and soil permeability on stability. However, the analysis is carried out using degree of saturation rather than suction.

McFarlane (1981b) attempted to predict suction from actual measured data mentioned in section 3 above based on a curve fitting and shifting method. This approach can best be treated as semi-empirical but would be useful for prediction if actual site specific measurement data are available.

The work of Anderson (1984) commissioned by the GEO was the first comprehensive attempt to predict suction in a rational manner by following the actual infiltration process in tiny time steps using an explicit finite difference computer program. To do this the following input were required

(a) for each soil element:

- moisture suction relationship
- saturated and unsaturated permeability
- porosity

(b) for the whole slope:

- distribution of soil strata
- initial conditions (distribution of suction)
- boundary conditions, especially at the top surface. Factors such as evaporation rate, transpiration of vegetation are also relevant.

As for all computer modelling it was soon realised that the crucial factor in terms of the reliability of the results of computer modelling is primarily the quality of the input. The moisture suction relationships of various specimens of a grade V weathered granite (28 remoulded and 6 natural specimens) and a grade V-VI weathered tuff (18 remoulded and 12 natural specimens), the two “reference materials” in those days, were determined up to 500 kPa suction in the Public Works Central Laboratory (PWCL) and these were reported in McFarlane (1981a). Most of the results are for drying only up to 200 kPa suction using the pressure plate extractor while some drying and wetting curves were obtained using the volumetric pressure plate extractor. The effect of hysterises was found to be not important for low suctions up to 200 kPa compared to other uncertainties and was not accounted for in the modelling, though it would not be too difficult to incorporate it. It should be noted that the suction moisture relationships were determined under unconfined conditions in the pressure plate extractor, and bound to lead to excessive swelling on wetting when compared to field behaviour. Some data under confining pressure were obtained for the granitic soil using the triaxial cell. Recently moisture suction relationships of more Hong Kong soils were determined in the University of Saskatchewan under the supervision of Professor Fredlund.

Unsaturated permeability (as a function of suction) was not determined but inferred from the moisture suction relationship and the saturated permeability, and several methods have been suggested in the literature. This is the approach adopted for most research on unsaturated soils and wildly accepted by researchers in the field. Errors introduced are small compared to other uncertainties. Fredlund et al (1994) indicated excellent agreement with laboratory measurement could be obtained from such methods. This is now being applied to the moisture suction relationships of Hong Kong soils by Professor Fredlund and the results obtained will be compared to unsaturated permeability, determined experimentally.

The boundary conditions at the top of the slope surface is an important input for the model, and this has led to two major supporting studies. Premchitt et al (1992) described the runoff study in which the coefficient of runoff were measured on various slopes in the field, and obtained runoff coefficients of about 0.9 for chunamed slope surface and 0.5 for vegetated surface. Anderson & Shen (1987) described how cracked chunam could be modelled, and indicated that severely cracked chunam could offer little protection against infiltration. However, little could be done regarding the soil permeability profile or distribution in the highly heterogeneous local soil. If the permeability profile is known accurately, then effects of perched water table etc. could easily be modelled in the computer.

The model in Anderson (1984) is basically one dimensional for infiltration (and two dimensional for ground water flow). Despite its simplicity it is capable of giving fairly good predictions. Figure 3 shows some results from the report. It should be noted however, the first point is the initial condition and does not require prediction. The conclusion of the study is that for slope well protected from direct infiltration, then suction can be expected.

Some very general but revealing information were also obtained from the result of the study, one of which is shown in Figure 4. This shows that in one-dimensional infiltration, in order to maintain suctions of the order of 6, 15 and 40 kPa for a local soil similar to the decomposed granite at King's Park, the effective permeability of the protective cover should be 2, 3 and 4 orders of magnitude less permeable than the soil. Also the rise in static ground water table from a given amount of infiltration could be derived from the moisture suction relationship, giving a more reliable estimate than the "wetting band" theory.

To conclude this section, much valuable work has been carried out in the understanding of moisture movement in unsaturated soils during this period, both locally and overseas. The work of Fredlund & Rahardjo (1993) offer a complete theoretical framework for understanding the behaviour of unsaturated soils. In terms of computer modelling,

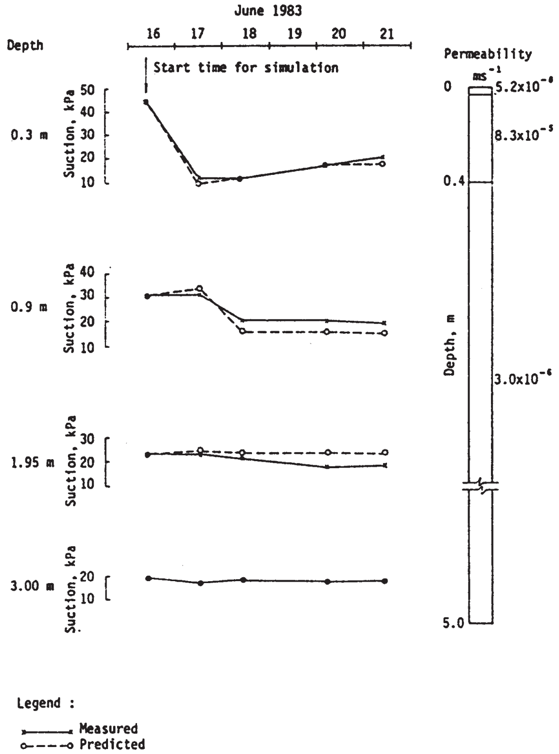

Figure 3. Comparison of measured and predicted suction (location C in Figure 2), after Figure 6.6 of Anderson (1984)

the rapid development in the area makes it possible to have commercial software such as "SEEP/W" which is able to handle with ease combined saturated and unsaturated flow. Our ability for prediction is now limited basically by our knowledge of the soil profile and its properties, rather than a lack of suitable theoretical model.

5 SUCTION AND SHEAR STRENGTH

Even if it can be shown that suction could exist in the slope during or after a severe rainstorm there remains the question how would it affect the shear strength. Testing on unsaturated soils was carried out in GEO as early as 1978. However, the results were not subjected to special interpretation other than assuming to be full effective stress as in saturated soils or using Bishop's ψ factor approach (GCO 1982). Ho (1981) is probably the first systematic study on the effect of suction on shear strength using suction as a stress state variable and some of the results were published in Fredlund (1981). This triggered a series of research into the shear strength of unsaturated soils in the GEO and the results of the work done between 1978 and 1982 were reported in Shen (1985). Besides

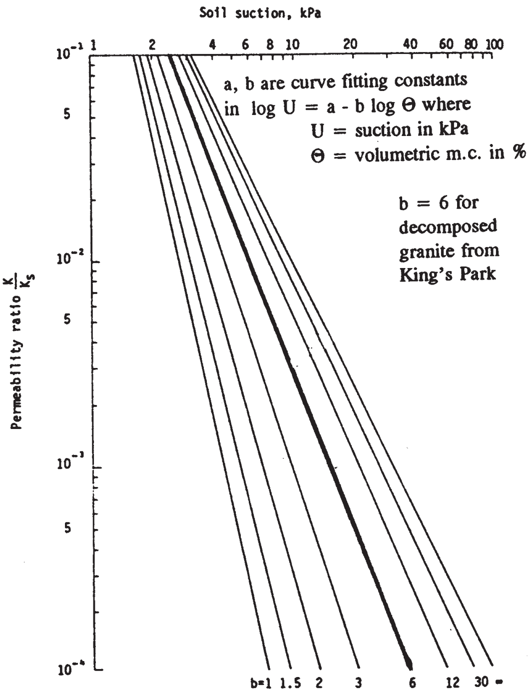

Figure 4. Prediction of the effect of a protective cover for maintaining suction, after Figure 5.2 of Anderson (1984)

a comprehensive literature review, test results reported include direct shear test (suction not measured, degree of saturation was the parameter adopted instead), triaxial compression test at constant moisture content (undrained) with measurement of suction, triaxial compression test with controlled constant suction (drained) and "dead load" test with failure induced by reducing suction. The latter test was triggered by ideas in Brand (1981), as providing the correct simulation of a rain induced failure. The tests clearly indicated that for the steep slopes in Hong Kong, there are threshold suctions below which failures would be triggered. Figure 5 shows such a test result. The specimen (a natural decomposed tuff) was able to stand up for 5 days at a suction of 3.5 kPa, and failed within 24 hours when the boundary suction was reduced to 0.

The research on shear strength of unsaturated soils was later passed to consultants to carry out. Gan & Fredlund (1991 & 1996) are reports produced under the consultancy for testing weathered tuff and weathered granite respectively.

It is now generally accepted that the increase in strength with suction is not linear as shown in Figure 6, which is reproduced from Gan & Fredlund (1991). Initially when the soil remains fully saturated suction may be considered as simply adding to the effective stress. As suction increases the soil becomes unsaturated and the pore water pressure only acts on part of the area, and hence there will be a reduction in the increase in shear strength with suction. This is the classical Bishop's ψ factor approach which is still being pursued by many, and which no doubt forms an important part of the theory of shear strength of unsaturated soils.

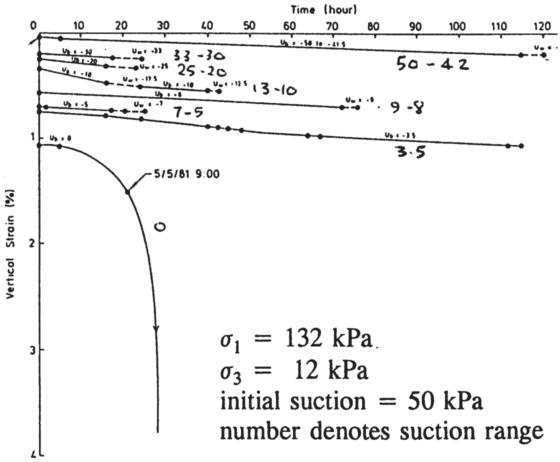

Figure 5. Dead load test on a specimen of natural decomposed tuff, after Figure 6.3 of Shen (1985)

However, the actual behaviour of unsaturated soil, such as the collapse of a loose soil on wetting, is much more complicated than could be explained by the ψ factor approach and that is why suction needs to be considered as a separate stress state variable. One significant conclusion of Shen (1985) is that a significant contribution of suction to shear strength is the increased dilatancy of unsaturated soil compared to saturated soil at the same confining total stress, probably as a result of aggregation of soil particles. This could not be explained by the ψ factor approach. Although the phenomenon was recorded

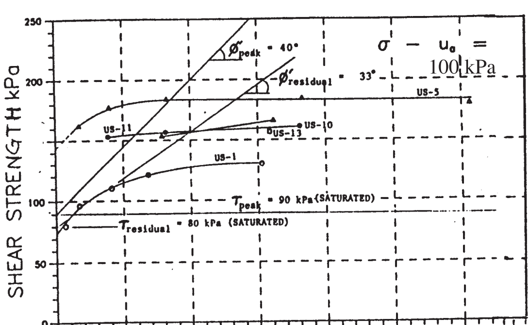

Figure 6. Shear strength versus suction relationship of a decomposed fine ash tuff at a net constant net normal stress of 100 kPa, after Figure 113 of Gan & Fredlund (1991)

in many results in the literature, they appeared not have been analysed in detail. In terms of critical state soil mechanics, it would appear that the critical state line at constant suction changes as suction is changed, forming a critical state surface in the three dimensional plot with suction included as one of the axis as a state stress variable. A possible explanation is that aggregation of particles are formed as suction increases, making the soil to behave as a more coarse grained soil, especially at low stress levels when these aggregations could be preserved.

Testing of more soil types is required to give a better understanding of the shear strength of unsaturated soils. For testing unsaturated soils at low suction, elevated air pressure is not required and conventional equipment could be used for testing unsaturated soils after very simple modification and is within the capability of local organisations. Modification required for the triaxial apparatus is described in Shen (1985). Modifications for the direct shear apparatus are even simpler, it only requires replacing the porous plate with a high air-entry ceramic connected to a pore pressure transducer to measure suction. It is recommended development in this area to be carried out focused on the Mazier sample, which has become the "standard" soil sample in Hong Kong, and have more soils tested locally.

6 USE OF SUCTION IN SLOPE DESIGN

Despite all the research described above, the use of suction in slope design is not yet a standard practice. It is understandable that authorities would not accept its contribution in design unless there are sufficient field evidence to demonstrate its existence for the particular site, while the designer would not like to base its design on the results of measurement, especially for the local environment where usually the time allowed for design is minimal. However, suction may have been indirectly taken into account in design using the back analysis approach, as described in Chang (1979).

7 CONCLUSIONS

In this paper the research work carried out locally on soil suction in relation to slope stability in the period 1978-1997 has been described. Hong Kong is certainly playing a leading role in certain areas of the research. It is hoped that the vast amount of information gathered and work done on the subject would not become forgotten. Perhaps this paper could renew interest on the subject.

ACKNOWLEDGEMENTS

This paper is published with the permission of the Director of Civil Engineering of the Hong Kong Government. The author is grateful to all those who have contributed to the study of suction in relation slope stability. This paper would not be possible without their work.

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