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Effects of soil suction on dilatancy of an unsaturated soil

Les effets de la succion du sol sur la dilatance d'un sol non saturé

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ABSTRACT

There has been a growing interest in studying and modelling unsaturated soil behaviour over the last 15 years. It is generally believed that soil suction affects dilatancy of unsaturated soils and some suction-dependant dilatancy relationships are assumed in many flow rules of existing elasto-plastic models. However, limited laboratory data reported in literature explicitly illustrate how suction affects dilatancy of an unsaturated soil during shear. In this paper, a series of laboratory tests on a compacted completely decomposed granite (CDG) were carried out in a suction-controlled direct shear box. Five suctions varying from 0 to 400 kPa were considered. Each specimen was wetted to close to its full saturation and then dried to a pre-determined soil suction before shear. During shear, each specimen was subjected to a constant net vertical stress and suction. Effects of soil suction on the evolution of dilatancy, stress dilatancy relationship and maximum dilatancy are presented and discussed in this paper.

RÉSUMÉ

Il y a eu un intérêt croissant en étudiant et en modelant le comportement du sol non saturé au cours des 15 dernières années. On le croit généralement que la succion du sol affecte la dilatance des sols non saturés et quelques rapports de dilatance dépendant de la succion sont assumés dans beaucoup de règles d'écoulement des modèles élasto-plastiques existants. Cependant, les données limitées de laboratoire rapportées en littérature illustrent explicitement comment la succion affecte la dilatance du sol non saturé pendant le cisaillement. Dans cette étude, une série d'essais en laboratoire sur un granit complètement décomposé compacté (CDG) a été effectuée dans une boîte de cisaillement à succion contrôlée. Cinq succions changeant de 0 à 400 kPa ont été considérées. Chaque échantillon a été mouillé à près de sa pleine saturation et puis séché à une succion prédéterminée avant le cisaillement. Pendant le cisaillement, chaque échantillon a été soumis à une succion constante et à une contrainte verticale nette constante. Des effets de la succion sur l'évolution de la dilatance, du rapport de dilatance de contrainte et de la dilatance maximum sont présentés et discutés dans cet exposé.

1 INTRODUCTION

Soil behaviour is influenced by dilatancy and so it is an important and essential component in elasto-plastic modelling of soils. Dilatancy in saturated soils has been studied for many years. It is fairly well understood. On the other hand, due to the complexity and long duration of testing unsaturated soils, fundamental understanding of the role of dilatancy in unsaturated soils is rather limited. Most of existing unsaturated constitutive models treat dilatancy using an assumption or deriving it from assumed yield surfaces with associated or non-associated flow rules (Alonso et al., 1990; Wheeler and Sivakumar, 1995). Recently Chui & Ng (2003) have introduced state-dependent dilatancy in their elasto-plastic model. However, relatively very limited and reliable laboratory data are available for verifying assumptions and calibrating constitutive relationships for unsaturated soils.

Cui & Delage (1996) performed three series of unsaturated triaxial tests on compacted silt under an osmotically controlled suction technique. Their test results obtained at mean constant stress ratio ($\eta = q/p = 1$) or at constant cell pressure under various suctions are shown in Figs 1a and 1b, respectively. Based on the results shown in Fig. 1a, they drew two conclusions: first, the ratio $d\varepsilon_v^p / d\varepsilon_s^p$ and hence the flow rule is independent of suction; second, the final value of $d\varepsilon_v^p / d\varepsilon_s^p$ is equal to 1. For constant cell pressure cases (Fig. 1b), they interpreted their data by separating these curves into two segments, i.e., one segment with small slope gradients for low η values and the other one with large slope gradients for higher η values. Based on a volumetric criterion, they claimed that the η values at intersection points of these two segments corresponded to yield points. They also claimed that in the plastic zone beyond the intersection points, the gradient of these slopes are independent of suction, thus a linear and suction-independent stress-dilatancy relationship is derived.

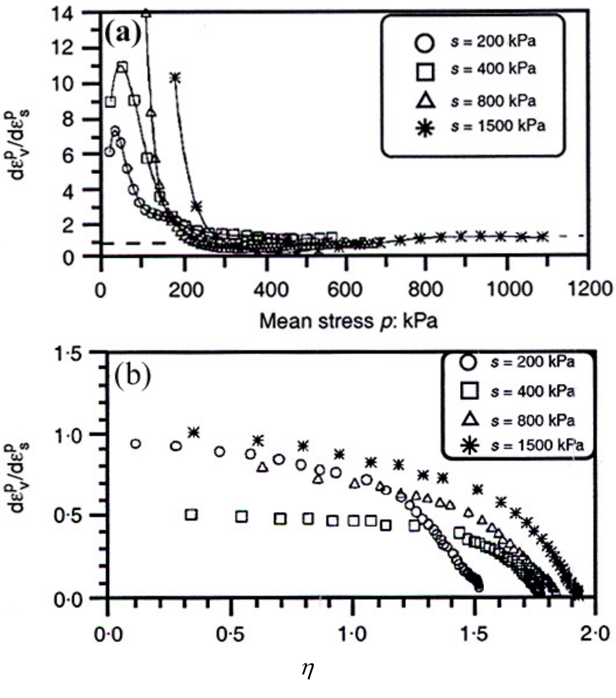

Figure 1. Effect of suction on dilatancy of silt under (a) constant stress ratio ($\eta = 1$) and (b) constant cell pressure ($\sigma_3 = 200kPa$) (after Cui & Delage, 1996).

Recently Chiu (2001) and Chiu & Ng (2003) have investigated stress-dilatancy of a decomposed volcanic soil and a decomposed granitic soil using a computer-controlled traixial apparatus. Fig. 2 shows experimental relationships of dilatancy ($d\varepsilon_v^p / d\varepsilon_s^p$) and normalised stress ratio (η/M) obtained by shearing decomposed volcanic soil specimens using constant water content stress paths. Following the same approach proposed by Cui and Delage (1996), no distinct yield point can be identified. At high stress ratios, the experimental data formed two groups according to their suction values. If an average line is drawn through these two groups of data at η/M=0.8 or higher, the gradients of these two fitted lines may be assumed to be parallel. This implies that the dilatancy rate with respect to η/M is independent of suction.

In this paper, a series of five laboratory tests on a compacted completely decomposed granite (CDG) were carried out in a suction-controlled direct shear box. Five suctions varying from 0 to 400 kPa were considered. Effects of soil suction on the evolution of dilatancy, stress dilatancy relationship and maximum dilatancy are investigated.

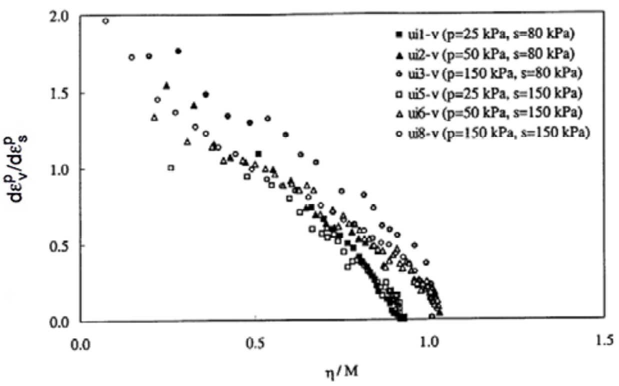

Figure 2. Stress-dilatancy relationship for specimens of decomposed volcanic soil under constant water content stress path (after Chiu, 2001).

2 SOIL TYPE AND TEST PROCEDURE

The soil used in the experiment was sieved CDG from Beacon Hill (BH), Hong Kong. Based on visual inspection, the BH soil was a coarse-grained sand with 22% silt and 2% clay. The soil was sieved into its constituent particle sizes. Dry sieving was performed and particles larger than 2mm were discarded in the tests. Index properties were determined in accordance with BS1337 (BSI, 1990). The material has a liquid limit, $w_L = 44\%$ %, and a plastic limit, $w_P = 16\%$. According to Proctor compaction test results, the maximum dry density was 1845 kg/m^3 and the optimum water content was 14.2%. The drying soil water characteristic curve (SWCC) for the CDG is shown in Fig. 3. Also included in this figure is a drying SWCC of a silty soil from Nishimura & Fredlund (2000). Air entry and residual suction values were determined using an equation proposed by Fredlund & Xing (1994) and are summarized in Table 1. The major difference between the two SWCCs is that the silt has a steeper SWCC than CDG does. This indicates that the silt has a more uniform particle size distribution than that of CDG. Any relationship between the SWCCs and shear test results are discussed later.

An unsaturated direct shear apparatus was used to carry out a series of unsaturated soil tests. The apparatus was originally developed by Gan et al (1988) and modified by Zhan (2003) in order to facilitate the measurements of water volume change automatically and accurately. The axis translation technique was utilized to control pore-air and pore-water pressures applied to a soil specimen.

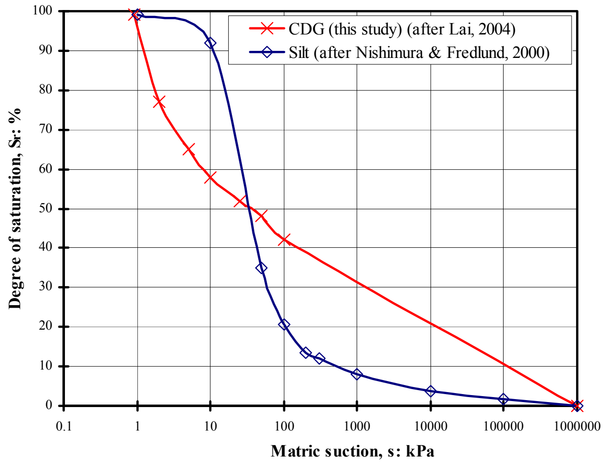

Figure 3. SWCCs of two soils

Table 1: Air entry values and residual suction values of two soils

Soil type	Air entry value, kPa	Residual suction value, kPa
CDG	1	1258
Silt	10	200

A series of five unsaturated direct shear box tests on recompacted CDG were conducted at various controlled suctions. Specimen with 50×50×21mm^3 (length×width×height) was used in the tests. Each specimen was prepared by static compaction technique and compacted at the optimum water content of 14.2%. The compacted initial dry density was 1.53 g/cm^3, corresponding to 82.7% of the maximum dry density.

After static compaction, each specimen was placed in the chamber of the unsaturated shear box equipped with a high air entry value of 500kPa ceramic disk, which was saturated according to the procedure proposed by Fredlund and Rahardjo (1993). Then the specimen was soaked under zero total vertical stress over 24 hours as illustrated in the path A→O in Fig. 4. Then the specimen was loaded along path O→B to a constant vertical normal stress (σ_v-u_a) of 50kPa, where σ_v is total vertical stress and u_a is pore air pressure. Subsequently, pore-air pressure was applied at the top of the specimen step up step while maintaining zero pore water pressure at the base of the specimen till a target air pressure was reached. Once the target air pressure was reached, suction equalization was monitored by recoding changes of water volume. When the change of water volume was less than 0.01% of initial water content, this suction equalization stage was terminated. Then shearing was carried out at a constant suction (i.e., along paths (B→B', C→C', D→D', E→E' and F→F').

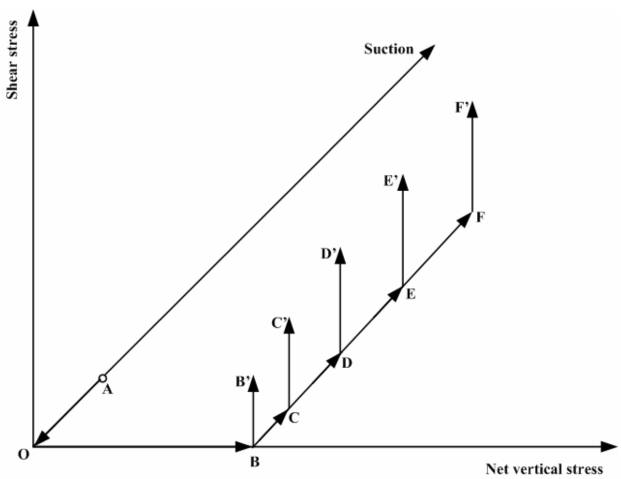

Figure 4. Stress paths in direct shear box tests.

3 DISCUSSION ON TEST RESULTS

3.1 *Evolution of dilatancy during shear*

Figs 5a and 5b show the relationships of stress ratio ($\tau/(\sigma_v-u_a)$) and dilatancy versus horizontal displacement (δx) respectively. In the figure, dilatancy is defined as the ratio ($\delta y/\delta x$) of incremental vertical displacement (δy) to incremental horizontal displacement. Negative sign (or negative dilatancy) means expansive behaviour. In Fig. 5a, it can be seen that at zero suction and suctions of 10 kPa and 50kPa, the stress ratio-displacement curve displayed strain hardening behaviour. With an increase in suction, strain softening behaviour was observed at suctions of 200 kPa and 400 kPa. Generally, measured peak and ultimate stress ratios increased with suction, except the ultimate stress ratio measured at suction of 200 kPa. These test results are consistent with existing elasto-plastic models (e.g. Alonso et al., 1990; Wheeler & Sivakuma, 1995; Chiu & Ng, 2003) for unsaturated soils.

Fig. 5b shows the effects of suction on dilatancy of CDG in the direct shear box tests. Under the saturated conditions, the soil specimen showed contractive behaviour (i.e., positive dilatancy). On the other hand, under unsaturated conditions, all soil specimens displayed contractive behaviour initially but then dilative behaviour as horizontal displacement continued to increase. The measured maximum negative dilatancy was enhanced by an increase in suction. This measured trend was consistent with test results on a compacted silt reported by Cui & Delage (1996). The increase in maximum negative dilatancy was likely attributed to a closer particle packing (i.e., a smaller void ratio) under a higher suction. At the end of each test, dilatancy of all specimens approached zero, indicating the attainment of the critical state.

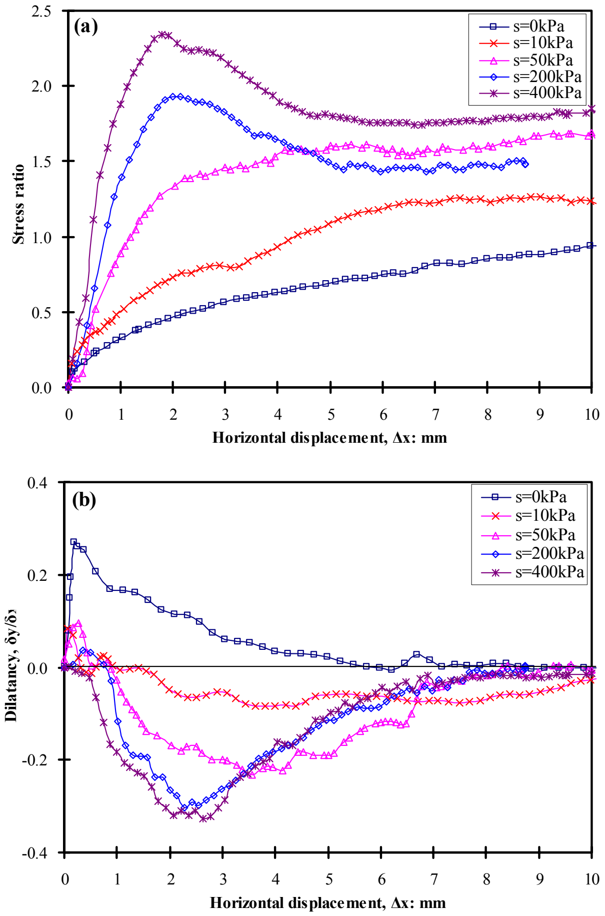

Figure 5. Evolution of stress ratio and dilatancy of CDG subjected to shear under different controlled suctions.

An interesting phenomenon observed in Fig. 5 was that strain hardening was recorded at suctions of 10 and 50 kPa as soil dilated. A maximum negative dilatancy at the latter test did not lead to strain softening behaviour. Another phenomenon observed was that when controlled suctions were equal to 200 and 400kPa, strain softening was observed (see Fig. 5a). However, the measured peak stress ratio in each test did not correspond with its maximum negative dilatancy (see Fig. 5b). This feature was not consistent with a common assumption in constitutive modelling that the point of peak strength was usually associated with the peak negative dilatancy in saturated granular materials (Bolton, 1986).

3.2 *Stress-dilatancy relationship*

Fig. 6 shows the measured stress dilatancy relationships in the five tests. At low stress ratios (i.e., 0.2 or smaller), positive dilatancy was observed for all specimens. The soil contracted initially during shear. As the stress ratios increased, negative dilatancy was measured in all unsaturated soil specimens. Obviously there was a phase transformation from positive to negative dilatancy as stress ratio increased. It is evident that the stress ratio corresponding to a maximum negative dilatancy increased with soil suction. As shearing continued, all the unsaturated soil specimens reached or approached zero dilation (i.e., critical state) at the end of each test. At the critical state, the measured stress ratio increased with suction, except at suction equal to 200 kPa. This measured trend is consistent with test results published by Cui and Delage (1996) and Chiu (2001) as shown in Figs. 1 and 2 of this paper, respectively. It should be pointed out in Fig. 6 that a distinct loop was observed in tests with suctions equal to 50kPa or higher. This implies that a state-dependent dilatancy soil model (Chiu and Ng, 2003) is necessary to capture this type of soil behaviour.

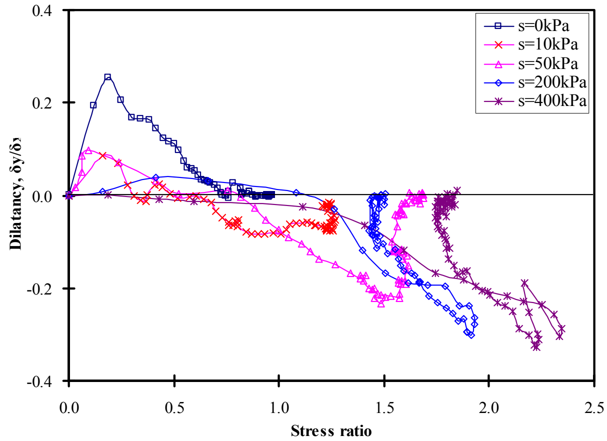

Figure 6. Experimental stress-dilatancy relationship.

3.3 *Maximum dilatancy*

Fig. 7 shows relationships of maximum dilatancy and controlled suctions for the CDG specimens. From comparisons, experimental data from unsaturated shear box tests on a silt from Nishimura (2000) are re-interpreted and included in the figure. Also included in this figure are the air-entry values and the residual suction values of these two soils. Their soil-water characteristic curves (SWCCs) are given in Fig. 3.

As illustrated in Fig. 7, maximum dilatancy of CDG decreases (i.e., more negative or dilative) with an increase in suction, i.e., the soil dilates more at a higher suction. The relationship between maximum dilatancy and suction is highly nonlinear. On the contrary, maximum dilatancy of the silt published by Nishimura (2000) increases (i.e., more contractive) linearly with suction. The major difference in the observed maximum dilatancy-suction relationships of these two soils is likely attributed to the difference in their initial soil densities (i.e., void ratios). The CDG and the silty soil have an initial dry density of 1.53 g/cm^3 and 1.27 g/cm^3, respectively. Therefore, it is not surprising to observe that CDG is more dilative than the silt for a given suction. By comparing the absolute values of the maximum dilatancy of these two soils, variations in the magnitude of the maximum dilatancy are relatively larger in CDG than that in the silt for a given change of soil suctions. In addition to the difference in the initial soil density, the compressibility of CDG is relatively large as compared with other silty soils because of the presence of crushable feldspar (Ng et al. 2004). Therefore, for a given increase in soil suctions, it is believe that CDG has undergone a larger reduction in void ratio than that in the silt, resulting in the measured larger absolute maximum dilatancy.

SWCC of a soil has been proposed and used to predict shear strength and many other properties of unsaturated soils (Vanapalli et al., 1996). Since the shear strength of a soil is closely related to its dilatancy, it is interesting to explore any correlation between the SWCCs of CDG and the silt and their corresponding maximum dilatancy. Based on the limited data shown in Fig. 3 and Fig. 7, it is very difficult, if not impossible, to draw any conclusion between measured maximum dilatancy and the SWCCs.

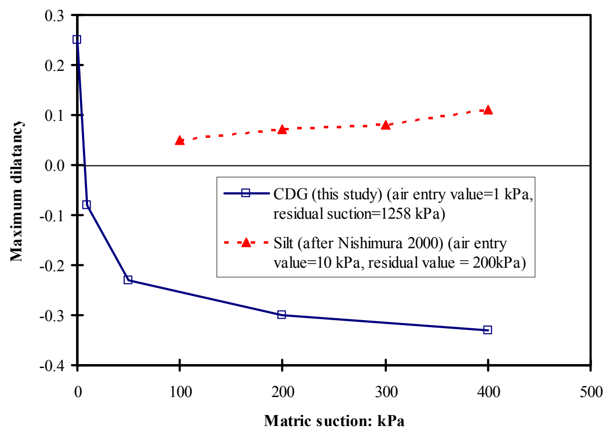

Figure 7. Relationship of maximum dilatancy with suction.

4 SUMMARY AND CONCLUSIONS

A series of consolidated drained shear tests were carried out on compacted CDG to investigate the effects of suction on shear behaviour and dilatancy. Measured stress ratio corresponding to a maximum negative dilatancy increased with soil suction. The measured peak stress ratio in each test did not correspond with its maximum negative dilatancy. Maximum dilatancy of CDG was strongly dependent on suction and soil density. The maximum dilatancy decreased (i.e., more negative or dilative) with an increase in suction, i.e., the soil dilated more at a higher suction. The relationship between maximum dilatancy and suction was highly non-linear. State-dependent flow rules are essential and vital for modelling unsaturated soils properly and correctly.

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