Behaviour of a compacted silty sand under constant water content shearing

Comportement d'un sable limoneux compacté sous cisaillement à teneur en eau constante

Heitor A., Rujikiatkamjorn C., Indraratna B.

Centre for Geomechanics and Railway Engineering, University of Wollongong, Wollongong, Australia ; ARC Centre of Excellence in Geotechnical Science and Engineering, Australia

ABSTRACT: The structure derived from compacting the soil at different water contents and energy levels can have a substantial effect on its shear strength. While the shear strength with varying suction can be estimated based on the saturated shear strength parameters and the unsaturated angle of shearing resistance (ϕ^b), limited studies have explored the variation of shear strength properties with different compaction states. In this paper, the shear strength of a silty sand soil was investigated using a conventional direct shear box under constant water content condition. The tests were conducted on specimens prepared by Proctor compaction with three different normal pressures. The shear strength parameters were obtained and modelled in terms of ultimate states.

RÉSUMÉ : La structure interne d'un sol résultante du compactage à différentes teneurs en eau et niveaux d'énergie peut avoir un effet important sur sa résistance au cisaillement. Alors que la résistance au cisaillement avec succion variable peut être estimée sur la base des paramètres de résistance au cisaillement en conditions saturées et de l'angle de résistance au cisaillement non saturé (ϕ^b), peu d'études ont exploré la variation des propriétés de résistance au cisaillement avec des niveaux de compactage différents. Dans cet article, la résistance au cisaillement d'un sol de sable limoneux a été étudiée en utilisant une boîte de cisaillement direct classique. Les tests ont été effectués sur des échantillons préparés par la méthode de compactage Proctor avec trois différentes pressions normales. Les paramètres de résistance au cisaillement ont été obtenus et modélisés en termes d'états ultimes.

KEYWORDS: Compacted soil, shear strength, constant water content, direct shear test.

1 INTRODUCTION.

Field compaction may not always be uniform (i.e. differences in hydration time, lift thickness and soil variability). Early studies have shown that these variations can have substantial effects on the mechanical behaviour of the compacted fine-grained soils (Proctor, 1933; Seed and Chan, 1956). The main aspects that can be affected are related to swelling, wetting induced collapse compression and soil response due to external loading (compression behaviour and shear strength).

Research studies on the shear strength behaviour of unsaturated compacted soil prepared at different compaction states (i.e. water contents and energy levels) showed that there is an intimate relationship between shear strength and water retention properties (i.e. Vanapalli et al. 1996). Furthermore, Wheeler and Sivakumar (2000) reported that a change in water content during compaction produces variations in the positions of the normal compression and critical state lines. Toll and Ong (2003) modelled the ultimate (critical) shearing behaviour of soil prepared at different initial compaction states and introduced the critical stress ratios as a function of the degree of saturation (S_r). Tarantino and Tombolato (2005) investigated the shear strength and hydraulic behaviour of statically compacted kaolin and showed that some of stress-strain behaviour features observed can only be modelled using hydro-mechanical coupling models.

While there has been an intensive research effort dedicated to the study of shear strength properties with varying post-compaction suction, limited research studies focussed on investigating the shear strength properties for different compaction states. This is undoubtedly important considering the lack of field compaction uniformity in terms of water content and energy. This paper presents the results from direct shear tests performed on compacted silty sand. The specimens were prepared at different compaction states in order to explore a broad range of initial conditions. Tests were carried out using a conventional direct shear box with the adoption of special measures to maintain constant water content conditions.

1.1 *Constant water content direct shear tests (CWDST)*

There are a number of different types of apparatus that can be used to study the shear strength behaviour of unsaturated soils. For testing soil under unsaturated conditions, the conventional apparatus often needs to be modified to enable the suction to be controlled or measured during the shearing stages, using i.e. axis translation technique, vapour equilibrium or osmotic suction control. While these types of control are effective, the laboratory conditions may not always be truly representative of those in the field, where shearing typically occurs under constant water content conditions. The use of the conventional direct shear box for determining the unsaturated shear strength parameters is very attractive because it is readily available to practitioners. Although it requires a careful moisture control, it can benefit from higher rates of shearing (compare 1μm/min for suction controlled apparatus with 0.005~1mm/min, i.e. Zhan and Ng 2006, Oloo and Fredlund 1996). The only drawback is the absence of an independent system to measure suction, although, Oloo and Fredlund (1996) and Cokca et al. (2004) assumed that any changes in suction during shearing would be minimal provided that a relatively fast rate of strain is adopted.

2 EXPERIMENTAL WORK

2.1 *Soil type*

The soil used in this study was silty sand classified as SP-SC (Unified Soil Classification System, USCS). The soil is a by-product of cobble quarrying activities that has been widely used to fill low areas at the Penrith Lakes site in Penrith (NSW, Australia). While the soils present on site are quite variable, for this study only a single grading was used. The particle size distribution was composed of 89% sand and 11% fines, of which 7% is silt and the remaining 4% is clay size particles. It has a liquid limit of 25.5%, a plasticity index of 10 and specific gravity of 2.7.

2.2 *Laboratory testing program*

The laboratory testing program included the execution of Proctor compaction tests (AS1289.5.1.1, 2003) under different levels of compaction energy (i.e. 15, 25, 35 blows per layer corresponding to 358, 596 and 834kJ/m^3). The required amount of water was added to the sample and the mixture was thoroughly mixed with a masonry trowel and then left under constant temperature and humidity conditions for 24h to ensure a uniform distribution of moisture. The compaction data is shown Figure 1. Subsequently, the specimens were carefully trimmed (60×60×25mm^3) from the compacted soil cylinders (1L) to minimize disturbance, while the excess of soil was typically used to determine the water content and suction using filter paper method and a small tip tensiometer. The procedure was completed in a matter of minutes to minimize exposure to air to prevent the loss of any moisture. Thereafter the specimens were wrapped in cling film and stored inside a plastic bag.

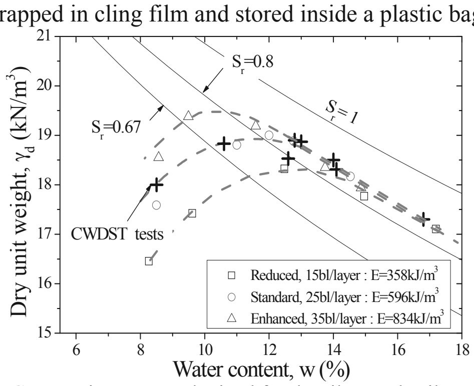

Figure 1. Compaction curves obtained for the silty sand soil.

2.2.1 *CWDST program*

A conventional shear box apparatus with a carriage running on roller bearings and a step motor drive unit capable of applying constant rate horizontal displacements was used. The apparatus was equipped with a load cell and two LVDT displacement transducers for measuring the horizontal shear force and monitor the horizontal and vertical displacements (accuracy of ±0.002kN, ±0.0025mm and ±0.001mm, respectively). A vertical load was applied with a lever arm loading system with beam ratio of 10:1. Data acquisition was controlled by a LabVIEW program coded “in house” accompanied with a National Instruments card NI USB-6009 with 8 input channels.

To conduct the tests under CW conditions, an effort was made to prevent any evaporation. This was achieved by running the compression and shearing stages of the tests in a temperature controlled environment (23±2^{o}C), and by enclosing the direct shear box with the assembly in an air tight plastic bag (Figure 2). Furthermore, to minimize the volume of air around the specimen, a 1mm thick film of polyethylene was placed in contact with the specimen and the gaps between the two sliding halves and the bottom half and base were sealed with silicone grease. The compacted specimens were extruded into the shear box and then subjected to a compression stage (vertical stresses of 38.4kPa, 79.5kPa, and 146.7kPa). Subsequently, the specimens were sheared at a constant rate of displacement of 0.01mm/min. It is important to note that in a direct shear test, the shear zone is localised and thin compared to the mass of the specimen (Shibuya et al. 1997). While suction is likely to be constant throughout the specimen when a small displacement rate is adopted due to self-equilibration, water content likely differs, but on average it would the same as the initial water content because water is not allowed to flow out and evaporation is minimised. This rationale is supported by the slight difference in suction measured using filter paper method (ASTM D5298, 2003) at the beginning and end of the tests (<5kPa and <1kPa for specimens prepared at dry and wet of OMC, respectively) and a small vertical variation of water content typically less 0.2-0.3% obtained in the sheared specimen at the end of the test.

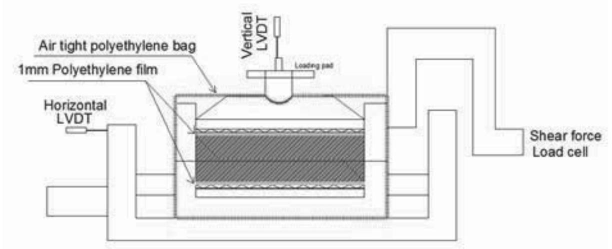

Figure 2. Shear box diagram with the system implemented to prevent evaporation.

3 RESULTS AND DISCUSSION

3.1 *As-compacted water content and suction*

Figure 3 shows the water retention data for additional compacted specimens prepared at different energy levels. Overall, the suction decreases with an increasing water content varying between 5 kPa to 616 kPa. Although there is no apparent relationship between suction and compaction energy, all data points seem to converge to a logarithmic regression line given by Eq. (1) ($R^2 > 0.95$).

$$w(s) = -1.56\ln(s)+18.50 \qquad (1)$$

This indicates that the hydraulic behaviour of compacted soil may be independent of the compaction characteristics (i.e. change in the water content and energy level).

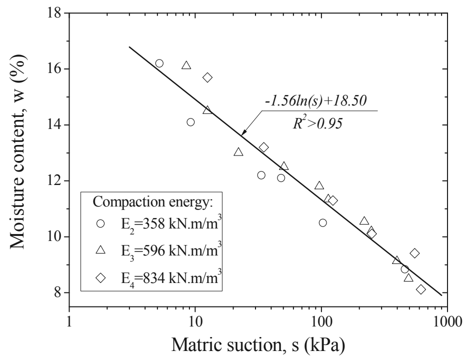

Figure 3. Post-compaction matric suction data in terms of water content.

3.2 *Shear strength behaviour*

In general, all the specimens showed a peak followed by a decrease in shear stress before subsequently attaining a relatively constant value after 6.5 mm of horizontal displacement. Although strain softening and dilative behaviour was clearly evident in the specimens compacted at dry of OMC, the specimens compacted at OMC and wetter of OMC did not show a distinct post peak drop and showed a mainly contractive response. Figure 4 shows the typical displacement plots obtained for an applied vertical stress of 40 kPa.

3.2.1 *Peak and ultimate shear strength envelopes*

Figure 5(a) shows the failure envelopes for the specimens prepared at same energy level but different water contents grouped by the correspondent applied vertical stresses. Both peak and ultimate states are represented and the envelopes were interpolated using the procedure suggested by Vilar (2006). While both peak and ultimate shear strength increase with suction in a non-linear fashion, the rate of increase seems to gradually decrease with increasing suction. Moreover, the envelopes seem to suggest the existence of a critical suction value, after which shear strength increase with suction is not very significant. For this particular study this value seems to be at suction of 100kPa, which corresponds to approximately 11.3% water content. It is interesting to note that the difference between the peak and ultimate shear strength envelopes increases with the applied vertical stress. This difference is probably due to the larger reduction in void ratio attained at the end of the compression stage for the specimens tested with higher vertical stresses. At the beginning of the test, these specimens have denser particle arrangement and would likely experience a more pronounced softening behaviour that in turn causes larger differences between the peak and ultimate shear strength. In figure 5 (b) the peak and ultimate shear strength data of specimens prepared at approximately the same water content is represented with the level of compaction energy. The peak shear strength seems to decrease with increasing energy while ultimate shear strength is less affected. This difference may be attributed to the fact that initial soil structure is being erased during shearing. The differences in peak shear strength are then probably associated with the difference in soil structure, particularly when the line of optima is exceeded (Figure 1, i.e. Kodikara, 2012). In addition, the specimens for whom the compaction end states are located on the wet side of the compaction plane may have experienced during compaction larger pore water pressures that were quickly dissipated. This in conjunction with the change in structure may contribute to the deterioration of the soil strength; however, further confirmation of this hypothesis is desirable.

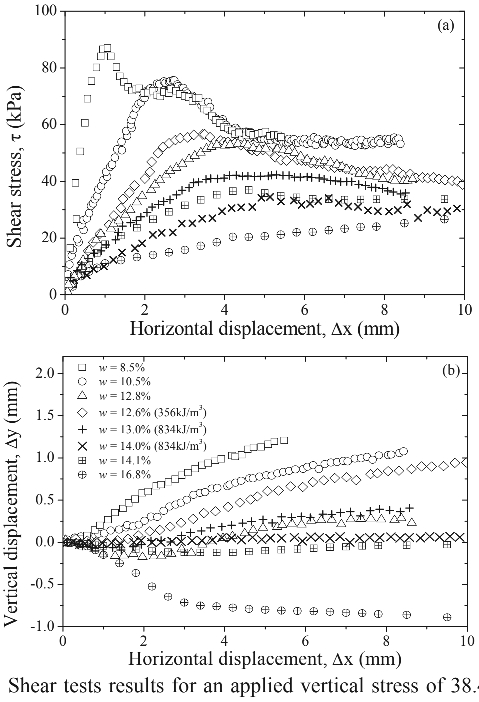

Figure 4. Shear tests results for an applied vertical stress of 38.4kpa in terms of (a) shear stress and (b) vertical displacement.(w =8.5~16.8% and E=358, 596 and 834kJ/m^3)

3.2.2 *Ultimate shear states*

The ultimate shear state results were modelled using two different approaches, namely, (a) the average skeleton stress (Tarantino and Tombolato, 2005) and (b) critical stress ratios (Toll and Ong 2003). Both approaches make reference to the saturated states which were found to be relatively independent of the compaction characteristics (Figure 6). Saturated tests were only conducted for specimens compacted at 12.5%, given the similarities of stress-strain behaviour between the saturated specimens and as-compacted specimens that reached saturation conditions during compression and shearing.

The average skeleton approach is based on the assumption that the water menisci have a negligible effect on the ultimate shear strength. The shear strength, τ , is given by considering the shear strength of saturated states at the same average skeleton stress τ_{sat} and the degree of saturation of the macropores, or S_{rm}, as follows:

$$\tau = \tau_{sat}\left(\sigma_v + sS_{rm}\right) = \tau_{sat}\left(\sigma_v + s\frac{e_w - e_{wm}}{e - e_{wm}}\right) \qquad (3)$$

where e_w and e are the water ratio ($e_w = e \times S_r$) and void ratio, respectively, and e_{wm} is the microstructural water ratio. The value of e_{wm} adopted is 0.237 and it was found by the least squares method fitting of Eq. (3). Figure 7 (a) shows the comparison between the measured and predicted ultimate shear strength for all specimens, considering the average skeleton stress defined in terms of S_r and S_{rm}. The prediction of shear stress is favoured by the adoption of the S_{rm} instead of S_r. Similar observations were reported by Tarantino and Tombolato (2005) for statically compacted kaolin, despite the fact that the fabric considered was mainly representative of the dry side of optimum.

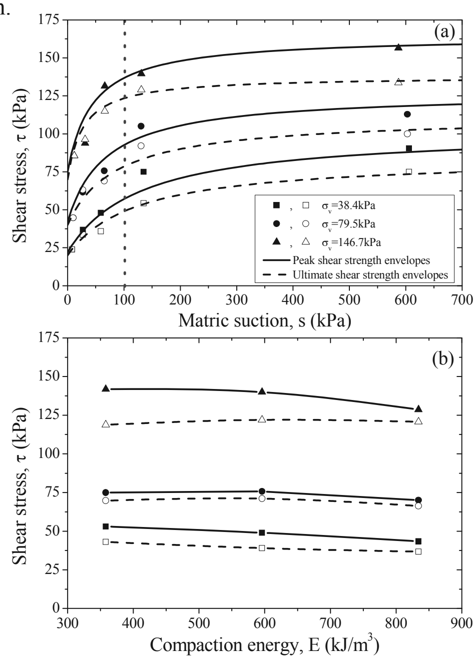

Figure 5. Shear strength envelopes for specimens compacted at (a) energy level of 596kJ/m^3 and (b) w=12.8~13% (close and open symbols represent peak and ultimate states, respectively).

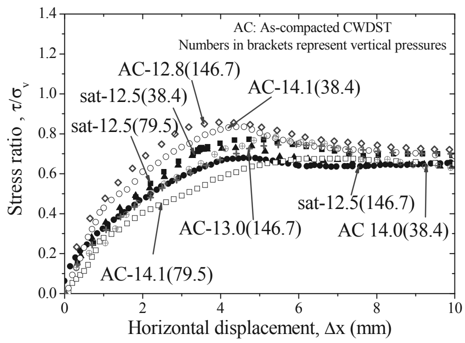

Figure 6. Stress ratio with horizontal displacement for saturated drained tests (w_c=12.5%, solid symbols) and constant water content test at high S_r (open symbols).

In contrast, in the critical stress ratio approach the contribution of the total stress and suction to the shear strength is considered separately (Toll and Ong, 2003). The soil fabric changes are reflected in the variation of two individual stress ratios governed by the degree of saturation. Toll and Ong

(2003) proposed the general shear strength relationship for critical state as follows

$$\tau = \sigma_v \tan\phi^a + s\tan\phi^b \qquad (4)$$

where, ϕ^a, ϕ^b, are the critical state friction angles in respect to the vertical stress, σ_v and suction, s. The critical state friction angles can be found using the following functions:

$$\frac{\phi^b}{\phi'} = \left(\frac{S_r - S_{r2}}{S_{r1} - S_{r2}}\right)^{kb} \qquad (5)$$

$$\frac{\phi^a}{\phi'} = \left(\frac{\phi^a}{\phi'}\right)_{\max} - \left[\left(\frac{\phi^a}{\phi'}\right)_{\max} - 1\right]\left(\frac{S_r - S_{r2}}{S_{r1} - S_{r2}}\right)^{ka} \qquad (6)$$

where S_{r1} and S_{r2} are two reference degrees of saturation and ϕ' is the saturated friction angle. For S_r exceeding S_{r1}, ϕ^a/ϕ' and ϕ^b/ϕ' ratios are equal to ϕ' whereas for S_r smaller than S_{r2}, $\phi^a/\phi' = (\phi^a/\phi')_{max}$ and $\phi^b/\phi'=0$. In this study the reference degree of saturation was taken as $S_{r1}=1$ (full saturation conditions) and $S_{r2}=0.75$, $kb=2$ and $ka=1$ (Figure 7 b).

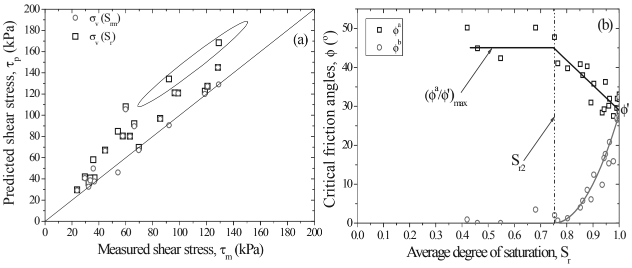

Figure 7. Prediction of (a) the ultimate shear strength using the average skeleton approach and (b) the critical friction angles with S_r measured at critical state.

The predictions of the ultimate shear strength obtained with the two approaches are shown in Figure 8. Although both approaches require approximately the same number of parameters, the critical friction angles approach seems superior in predicting the shear strength of soil prepared at a wide range of moisture contents and energy levels. The predictions may be considered satisfactory given that in this study a single set of parameters is used for modelling compaction states that differ in both water content and energy level and thus soil structure.

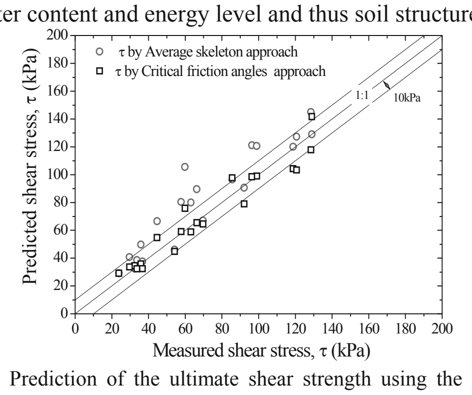

Figure 8. Prediction of the ultimate shear strength using the average skeleton approach and using the critical friction angles approach

4 CONCLUSION

This study presented the results on the shear strength of compacted silty sand using constant water content direct shear tests. The as-compacted water retention data showed that, regardless of the energy level applied during compaction, there is a unique relationship between water content and suction.

The peak and ultimate shear strength envelopes results show that there is a relatively well defined non-linear relationship between shear strength and matric suction. Also, the envelopes suggest the existence of critical suction, after which the shear strength increase is less significant. A decrease of peak shear strength was observed for increasing compaction energy that was interpreted to be associated with a difference in soil structure and the compaction history of the specimens.

Constant water content direct shear tests on saturated specimens show that the ultimate shear strength is relatively independent of the initial compaction state. The ultimate shear strength is modelled using two different approaches, that is, the average skeleton stress and independent critical stress ratios. The first is usually associated with the consideration of a Bishop type of effective stress whereas the latter considers the net stress and suction effect on the shear strength to be independent. Although both approaches provide reasonable estimations of shear strength, for this particular study the independent stress variables approach is superior. Worth noting that the prediction exercise catered for different compacted states and represents a step forward in understanding the implications of the inherent variability of compaction conditions on the soil shear strength.

5 ACKNOWLEDGEMENTS

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