Effect of Compaction History on the Shearing Behaviour of a Silty Sand Under Constant Water Content Conditions

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ABSTRACT: Compaction conditions govern the shear strength behaviour of a compacted soil. The shear strength parameters are usually evaluated for specimens compacted at a given state and then tested for different post-compaction loading conditions. While this approach enables the prediction of the behaviour in service, the impact of compaction history is usually ignored. This is an important aspect as the shearing behaviour of compacted soil is strongly influenced by soil structure and suction, and thus the soil's compaction/loading history. In this paper, the aspects related to the effect of compaction history of a silty sand soil subjected to direct shearing under constant water content conditions are described. To investigate the role of compaction history, specimens were prepared at different compaction energy levels and subsequently tested under the same vertical stress. The results confirm the importance of the initial stress state of the soil in relation to its compaction history in governing the mechanical response during direct shearing.

1 INTRODUCTION

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 (e.g. Vanapalli et al. 1996: Indraratna et al., 2012: Heitor et al., 2013a: Heitor et al., 2014a). 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 the post-compaction shear strength properties with varying post-compaction loading conditions, limited research studies focused on investigating the shear strength properties for different compaction loading histories. This is undoubtedly important as the shearing behaviour of compacted soil is strongly influenced by soil structure and suction, which in turn is impacted by the soil's compaction/loading history. This paper presents the results from constant water content direct shear tests (CWDST) performed on compacted silty sand. The specimens were prepared at different compaction energy levels and subsequently tested under the same vertical stress. Tests were carried out using a conventional direct shear box assembly and special care was taken to ensure constant water content conditions.

1.1 *Unsaturated shear strength via direct shear tests*

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 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), Cokca et al. (2004), Heitor et al. (2013b) and Indraratna et al. (2014) assumed that any changes in suction during shearing would be small provided that a relatively fast rate of strain is adopted.

2 EXPERIMENTAL WORK

2.1 *Soil Type and Laboratory testing program*

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). 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. The laboratory testing program included the execution of Proctor compaction tests under different levels of compaction energy (i.e. 15, 25, 35 blows per layer corresponding to 358, 596 and 834kJ/m^3). The compaction data is shown Fig. 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 tensiometer with miniature tip. The procedure was completed in a matter of minutes to minimize exposure to air to prevent the loss of any moisture.

2.2 *CWDST program*

A conventional shear box apparatus used was equipped with a load cell and two LVDT displacement transducers for measuring the horizontal shear force and monitoring the horizontal and vertical displacements (accuracy of 0.002kN, 0.0025mm and 0.001mm, respectively). 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°C), and by enclosing the direct shear box with the assembly in an air tight polyethylene bag (Fig. 2).

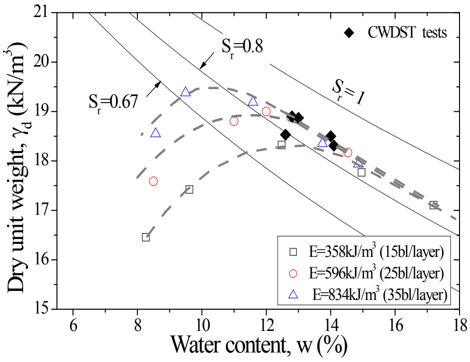

Fig. 1 Compaction curves obtained from the silty sand soil (modified after Heitor et al., 2013b).

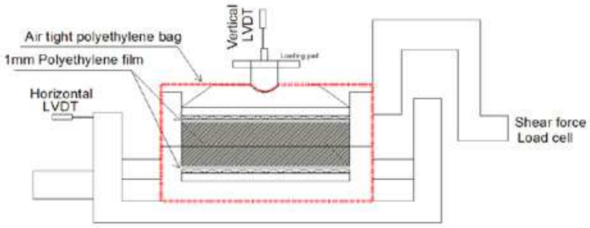

Fig. 2 Shear box diagram with the system implemented to prevent evaporation (Heitor et al., 2013b).

The compacted specimens were extruded into the shear box and then subjected to a compression stage (vertical stresses of 39kPa, 80kPa, and 150kPa). 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, 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 at the beginning and end of the tests (<1kPa) and a small variation of water content typically less 0.2-0.3% obtained in the sheared specimen at the end of the test.

3 RESULTS AND DISCUSSION

3.1 *Shear strength behaviour*

The effect of compaction energy level on the shear strength behaviour can be established if the specimens compacted at different energy levels are tested under the same vertical stress. The shear strength behaviour of the specimens prepared at various compaction energy levels and tested under the same vertical stress of 80kPa is shown in Fig.3.

Table 1. Summary of tests

Water content (%)	Vertical stress, σ_v (kPa)	Compaction energy, σ_c (kJ/m^3)	e	S_r
0.126	39	358	0.391	0.87
	80		0.365	0.93
	150		0.361	0.94
0.128	39	596	0.384	0.90
	80		0.356	0.97
	150		0.346	1.0
0.13	39	834	0.377	0.93
	80		0.365	0.96
	150		0.351	1.0
0.14	39	596	0.425	0.89
	80		0.409	0.92
	150		0.378	1.0
0.141	39	834	0.396	0.96
	80		0.388	0.98
	150		0.381	1.0

Note: The void ratio (e) and degree of saturation (S_r) values displayed refer to the end of the compression stage.

It can be observed that the stress-displacement response is similar but the specimens compacted at a lower energy level (E=356kJ/m^3) exhibit a more evident post-peak softening and dilative behaviour. In contrast, the specimens compacted at higher energy levels (E= 596 and 834 kJ/m^3) show just a slight post peak drop and mainly contractive response. The effect of the compaction energy level seems less important in those specimens prepared wetter of OMC (i.e. w ≈ 0.14).These results are not surprising and are likely associated with the initial soil macrostructure (Fig. 4) induced by the compaction process. Fig. 4 shows the CT-scan images obtained for specimens prepared approximately at 0.125 and different energy levels. White areas represent air filled and water filled pores, whereas the grey and dark areas correspond to aggregations and sand particles, respectively. Fig. 4 shows that the specimens near OMC still exhibit aggregated type of macrostructure (Fig. 4a) and as the level of compaction energy is gradually increased it changes to a matrix dominated macrostructure (Fig 4b and c) with the sand grains easily individualized in the matrix. Furthermore, while the water content is approximately the same for the three specimens at the end of the compression stage, this is not the case for the degree of saturation (Table 1). This is consistent with the observations of Tarantino and Tombolato (2005) that suggested that S_r together with suction govern the shear strength response of compacted soil.

3.2 *Peak and ultimate states*

Additional tests were carried out at different vertical stresses (i.e. 39 and 80kPa) to examine the effect of compaction energy level on the peak and ultimate shear strength envelopes. In Fig. 5, the peak and ultimate shear strength data of specimens prepared at approximately the same water content (i.e. w=0.128 ~ 0.13) 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.

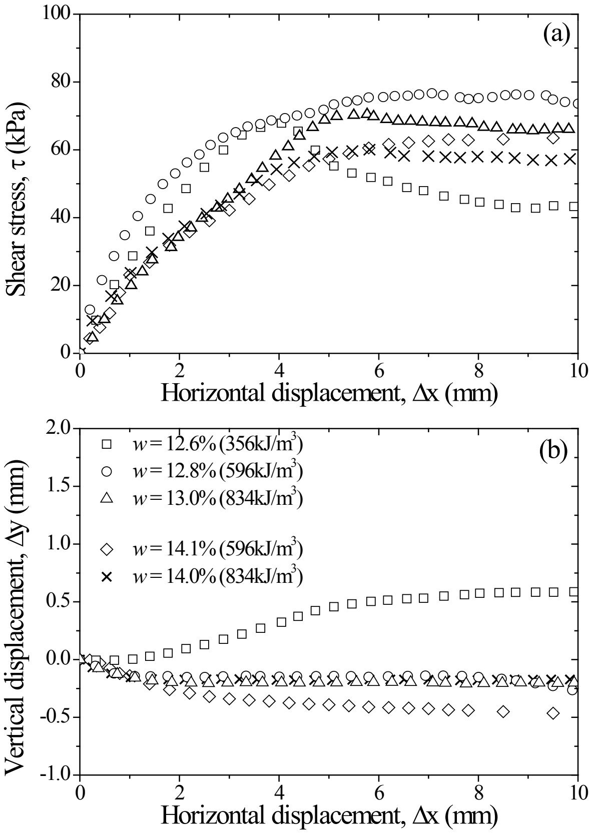

Fig. 3 Shear tests results for an applied vertical stress of 80kPa in terms of (a) shear stress and (b) vertical displacement.

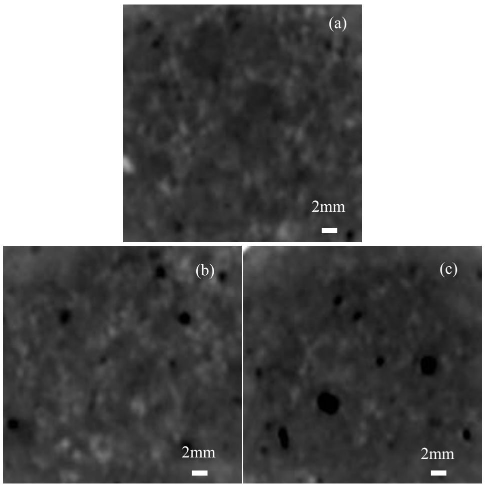

Fig. 4 CT-scan images of compacted specimens prepared at different compaction energy levels of (a) 356 kJ /m3, (b) 596 kJ /m^3 and (c) 834 kJ /m^3 (Heitor et al., 2013a).

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 (S_r=0.8) is exceeded (Fig. 1, i.e. Kodikara, 2012). In addition, the specimens with compaction end states 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.

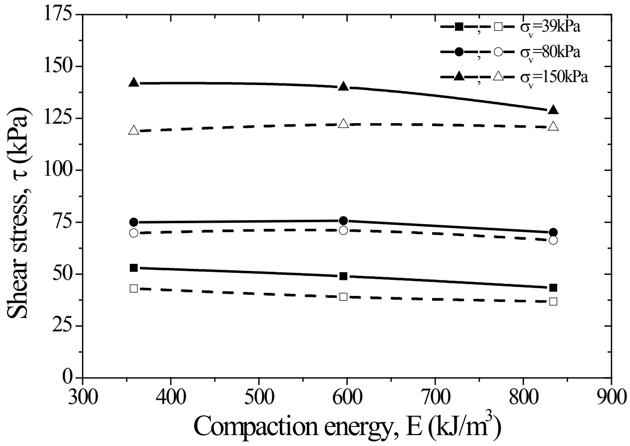

Fig 5. Shear strength envelopes for specimens compacted at w=12.8~13% (close and open symbols represent peak and ultimate states, respectively).

4 CONCLUSIONS

From a number of constant water content direct shear tests it was observed that the compaction energy for specimens tested under the same vertical stress governs their shear strength behaviour. However, the impact of compaction energy seems to be more evident for those specimens prepared on the dry side of the compaction plane, and this is likely associated with the progressive change in the soil structure. Furthermore, specimens compacted at lower energy exhibit a more pronounced strain softening behaviour and dilation compared with those compacted at larger energy levels. The effect of compaction energy on the peak and ultimate shear strength envelopes was also investigated. The peak shear strength seems to decrease with increasing compaction energy while ultimate shear strength is less affected. This was interpreted to be the result of the initial soil structure being erased during shearing. Finally this study shows that the shear strength of compaction soil is intimately its compaction energy level and should be considered particularly when common end-product specification are used.

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