Influence of compaction history on the shear strength behaviour of compacted soil

Comportement de résistance au cisaillement du sol compacté ayant des histoires de compactage différentes

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ABSTRACT: The condition under which soil is compacted governs its shear strength, which is why the shear strength parameters of specimens compacted at a given state are usually evaluated and tested for different post-compaction loading conditions. While this enables the behaviour to be predicted in service, the impact of the compaction history is usually ignored. This is an important aspect because how compacted soil behaves during shearing is strongly influenced by its structure and suction, and thus its compaction and loading history. In this paper the aspects related to the compaction history of a silty sand soil prepared by dynamic compaction and then tested with a direct shearing box are examined. To replicate an as-compacted condition, the specimens are tested under constant water content. To investigate the compaction history the specimens were prepared under different levels of compaction energy and then tested under the same vertical stress. The results confirm how important the initial stress state of the soil is in relation to its compaction history, in governing the mechanical response during direct shearing.

RÉSUMÉ : Les conditions de compactage régissent le comportement de cisaillement d'un sol compacté. Les paramètres de résistance au cisaillement sont habituellement évalués pour des spécimens compacts à un état donné, puis testés pour différentes conditions de post-compactage. Bien que cette approche permette de prédire le comportement du sol, l'impact de l'historique de compactage est généralement ignoré. C'est un aspect important puisque le comportement de cisaillement du sol compacté est fortement influencé par la structure du sol, et donc l'histoire de compactage / chargement du sol. Dans cet article, nous examinons les aspects relatifs à l 'effet de l' histoire de compactage d 'un sol de sable limoneux testé à une caisse de cisaillement direct. Pour reproduire l'état compacté, les échantillons ont été testés dans des conditions de teneur en eau constantes. Pour étudier l'influence de l'histoire du compactage, des échantillons ont été préparés à différents niveaux d'énergie de compactage et testés par la suite sous la même contrainte verticale. Les résultats confirment l 'importance de l' état de contrainte initial du sol par rapport à son histoire de compactage dans la régulation de la réponse mécanique lors du cisaillement direct..

KEYWORDS: Compaction history, constant water content, shearing behavior of compacted soil.

1 INTRODUCTION

Research studies on the shear strength of unsaturated compacted soil prepared at different compaction states (i.e. the water content and energy levels) show there is an intimate relationship between the shear strength and water retention properties (e.g. Vanapalli et al. 1996, Indraratna et al., 2014, Heitor et al, 2014a, Heitor et al., 2014b, Heitor et al., 2015a). Furthermore, Wheeler and Sivakumar (2000) reported that any change in the water content during compaction produces variations in the positions of 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 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 stress-strain features can only be modelled using hydro-mechanical coupling models. Despite the intensive research into post-compaction shear strength properties with varying post-compaction loading conditions, not many research studies focused on investigating the shear strength properties for different compaction loading histories. This is undoubtedly important because the shearing behaviour of compacted soil is strongly influenced by its structure and suction, which in turn is impacted by its compaction and loading history. This paper presents the results from constant water content direct shear tests (CWDST) carried out on compacted silty sand. The specimens were prepared at different levels of compaction energy and then tested under the same vertical stress. These 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*

The modifications carried out when testing unsaturated soil in a direct shear apparatus can be either active control, i.e., the suction is held constant throughout shearing, or passive control where the suction is measured independently under constant water content (CW) conditions. The most common method for active suction control uses the axis translation technique (e.g. Escario and Saez, 1986; and de Campos and Carrillo, 1995), which imparts varying matric suction ($s = u_a - u_w$) by changing the air pressure u_a, while maintaining a relatively constant water pressure u_w in an air tight cell. While this type of active control is effective, the design of external cells that can withstand high air pressure and remain air tight can pose mechanical difficulties because when a prescribed value of suction must be applied and maintained during shearing, displacement rates sometimes as low as 1μm/min must be adopted, which is very time consuming. Furthermore, the laboratory conditions may not always reflect those in the field where the air pressure is atmospheric and the water pressure is negative, which is why passive suction control techniques can benefit from higher rates of shearing and the air pressure is essentially atmospheric, despite the system being undrained for the water phase.

Caruso and Tarantino (2004) and Tarantino and Tombolato (2005) adopted two high capacity tensiometers (HCT) up to 1000kPa, while Jotisankasa and Mairaing (2010) used one tensiometer (up 100kPa) to measure suction independently. The modifications to the direct shear apparatus using this technique are not very complex so they are attractive from a practical point of view, but the suction for most fine grained soils exceeds 100kPa, which limits the choice of commercially available HCTs.

The use of a conventional direct shear box to determine the unsaturated shear strength parameters is very attractive because it is readily available to practitioners, and although 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) and Heitor et al. (2013b) assumed that any changes in suction during shearing would be small provided a relatively fast rate of strain is adopted. Furthermore, despite the results from a direct shear test (DST) being quite limited, unlike triaxial or simple shear, i.e. the lateral pressure and stresses on the planes other than the plane of shear are not known, its simplicity in terms of its operation and understanding its meaning is an important advantage.

2 COMPACTION HISTORY

The initial soil state may depart from the main wetting surface or the scanning unloading/reloading surfaces, so this distinction should be placed in the stress range to which the specimens are prepared and then subjected to direct shearing. While the effect of the loading history for specimens prepared and tested at constant suction affects the shear strength parameters, not many studies have addressed the impact of the loading history under constant water conditions.

The initial compacted soil states can be divided into two main groups depending on the compaction stress or energy level (σ_c), and the applied vertical stress (σ_v) during shearing (Figure 1), thus:

Group 1: These specimens were reloaded to the compaction stress state ($\sigma_c/\sigma_v = 1$) and the degree of saturation and suction corresponding to the virgin loading path. The specimens most likely to experience the largest degrees of saturation during shearing are represented by points A, B, and C.

Group 2: These specimens were reloaded to a smaller applied vertical stress than the compaction stress or equivalent energy level ($\sigma_c/\sigma_v > 1$), and the corresponding degree of saturation and suction are located on the unloading/reloading surface (i.e. points A_1, B_1, and C_1)

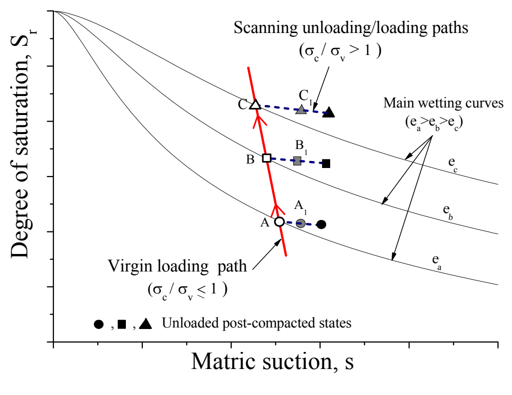

Fig. 1 Conceptual diagram showing the impact the loading history had on the state of the soil.

3 EXPERIMENTAL WORK

3.1 *Soil Type and Laboratory testing program*

The soil used in this study was silty sand classified as SP-SC (Unified Soil Classification System, USCS); it is a by-product of cobble quarrying activities and has been widely used as fill material in the low areas at the Penrith Lakes site in Penrith (NSW, Australia). The particle size distribution consisted of 89% sand and 11% fines, of which 7% is silt and the remaining 4% are clay size particles. It has a liquid limit of 25.5%, a plasticity index of 10, and a 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, respectively).

The compaction data is shown in Fig. 2a together with the respective suction contours. The specimens were trimmed (60×60×25mm^3) from the compacted soil cylinders (1l) to minimise disturbance and the excess soil was typically used to determine the water content and suction using the filter paper method and a tensiometer with a miniature tip. This procedure was completed in a matter of minutes to minimise exposure to air and to prevent any moisture being lost.

In this paper the specimens were compacted dynamically and thus the virgin loading paths (Fig. 1) cannot be defined, however the post-compaction stress states and those at the start can be mapped; they are shown in Fig. 2b and the results are shown in Table 1. Note that for this study only the data of specimens prepared at optimum moisture content (OMC) for the lowest energy level and wet side of the compaction plane is shown. In this range suction variation is more significant with increasing compaction energy, i.e. the suction contours in the dry side of the compaction plane are nearly vertical (Heitor et al., 2013)

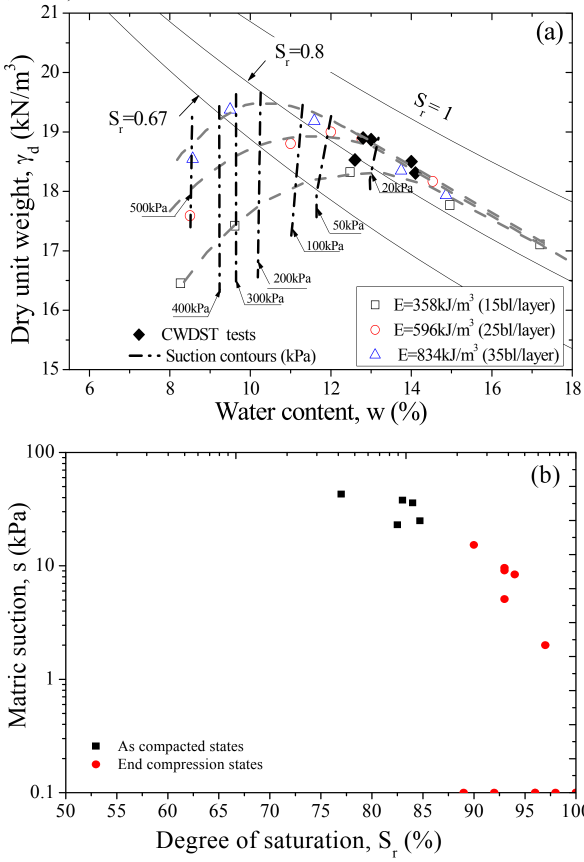

Fig. 2 Compaction data represented in (a) the γ_d-w space and (b) the S_r- s space.

3 .2 Constant water content direct shear test (CWDST) program

The conventional shear box apparatus was equipped with a load cell and two LVDT displacement transducers to measure the horizontal shear force and monitor the horizontal and vertical displacement (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 carry out the tests under constant water content (CW) conditions, evaporation was prevented by running the compression and shearing tests in a temperature controlled environment (23±2ºC), and by enclosing the direct shear box and the assembly in an air tight polyethylene bag (Fig. 3).

The compacted specimens were extruded into the shear box and then subjected to compression (vertical stresses of 39kPa, 80kPa, and 150kPa). The specimens were then sheared at a constant rate of displacement of 0.01mm/min.The test conditions are summarised in Table 1.

Table 1. Summary of tests

Water content (%)	Vertical stress, σ_v (kPa)	Compaction energy, E (kJ/m^3)	Suction (kPa)	e	S_r (%)
12.6	39	358	15.3	0.391	90
	80		2	0.365	97
	150		0.1	0.361	100
12.8	39	596	9.1	0.384	93
	80		9.6	0.356	93
	150		8.4	0.346	94
13	39	834	5.1	0.377	93
	80		0.1	0.365	96
	150		0.1	0.351	100
14	39	596	0.1	0.425	89
	80		0.1	0.409	92
	150		0.1	0.378	100
14.1	39	834	0.1	0.396	96
	80		0.1	0.388	98
	150		0.1	0.381	100

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

Note that during a direct shear test, while the suction is more likely to be constant throughout the specimen due to self-equilibration when a small displacement rate is adopted, the water content probably differs, but on average it would be 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 by the filter paper method at the beginning and end of the tests (<1kPa), and the small variation of water content, typically less 0.2-0.3%, that was obtained in the sheared specimen at the end of the test.

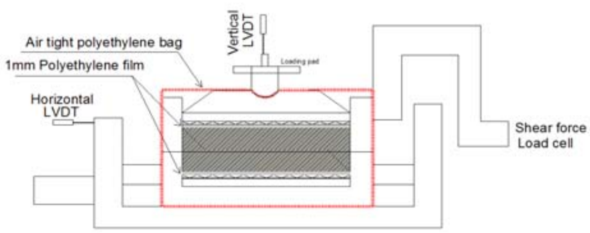

Fig. 3 Shear box diagram with the system implemented to prevent evaporation (Heitor et al., 2013b).

4 RESULTS AND DISCUSSION

4.1 *Shear strength behaviour*

The effect the compaction energy (i.e. compaction history) had on the shear strength can be established if the specimens are compacted at different levels of energy and tested under the same vertical stress. The shear strength behaviour of the specimens prepared at various levels of compaction energy and tested under the same vertical stress of 80kPa is shown in Fig. 4. Note here that the stress-displacement is similar but the specimens compacted at a lower energy level (E=356 kJ/m^3) exhibit more post-peak softening and dilative behaviour. However, the specimens compacted at higher energy levels (E= 596 and 834 kJ/m^3) show a slight post peak drop and mainly contractive response. The level of compaction energy seems to be less important in those specimens prepared wetter than OMC (i.e. w ≈ 14%).

These results are not surprising and are probably associated with the initial soil macrostructure, i.e. an aggregated type of macrostructure where, as the level of compaction energy gradually increased it change to a matrix dominated macrostructure (Heitor et al., 2013a). Furthermore, while the water content for the three specimens at the end of the compression stage is approximately the same, this is not the case for the degree of saturation (Table 1). This is consistent with the observations made by Tarantino and Tombolato (2005) which suggested that the S_r and the suction govern the shear strength of compacted soil.

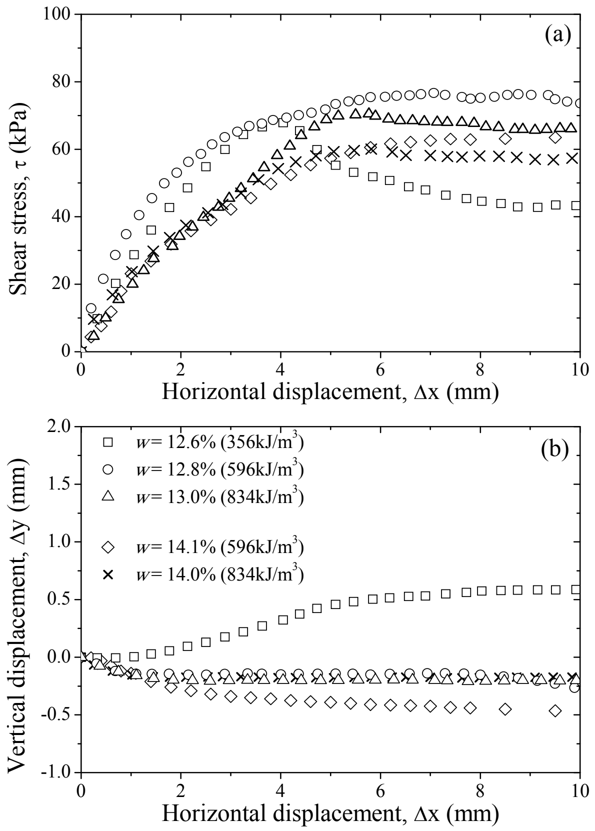

Fig. 4 Shear tests results for an applied vertical stress of 80kPa in terms of (a) shear stress and (b) vertical displacement.

4.2 *Peak and ultimate states*

Further tests were carried out at different vertical stresses (i.e. 39 and 150kPa) to examine how the level of compaction energy level (i.e. compaction history) affected the peak and ultimate shear strength envelopes. The peak states refer to the maximum shear stress attained whereas the ultimate states refer to the shear stress obtained at large displacements for which the variation of vertical displacements is small. In Fig.5, the peak and ultimate shear strength data of specimens prepared at approximately the same water content (i.e. w=12.8 ~ 13%) are shown with the level of compaction energy. Here the peak shear strength seems to decrease as the energy increases, whereas the ultimate shear strength is less affected.

This difference may be due to the initial soil structure being erased during shearing and if so 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). Moreover, those specimens with compacted end states located on the wet side of the compaction plane may have experienced larger pore water pressures during compaction that were quickly dissipated. In conjunction with the change in structure, this may contribute to the deterioration of the soil strength, but further confirmation of this hypothesis is needed. In addition, Fig. 5 indicates that for specimens prepared at OMC and wet of OMC, doubling the compaction energy provides little change in shear stress.

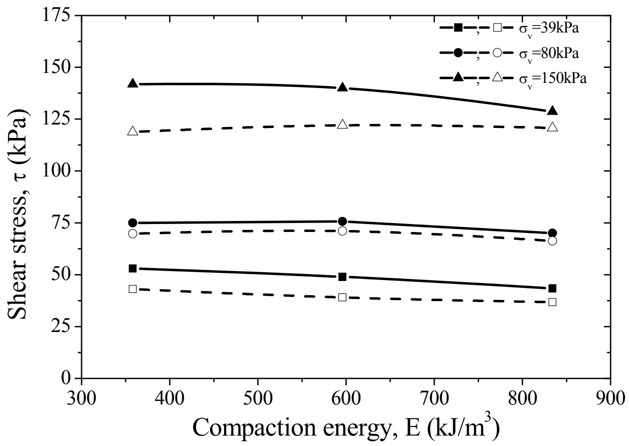

Fig 5. Shear strength envelopes for specimens compacted at w=12.8~13% (close and open symbols represent peak and ultimate states, respectively).

5 CONCLUSION

A number of constant water content direct shear tests revealed that the compaction history of compacted specimens prepared at different energy levels but tested under the same vertical stress, governs their shear strength behaviour. However, the impact of compaction energy seems more evident on those specimens prepared at the optimum moisture content (i.e. 357kJ/m^3), probably due to a progressive change in the soil structure. Furthermore, specimens compacted at lower energy exhibited more strain softening and dilation than those compacted at larger energy levels. The effect of compaction energy on the peak and ultimate shear strength envelopes was also investigated and indicated that the peak shear strength seems to decrease as the compaction energy increases, while the ultimate shear strength is less affected. This was interpreted as due to the initial soil structure being erased during shearing. Finally this study shows that the shear strength of compacted soil is ultimately its level of compaction energy and associated compaction history and therefore should be considered, particularly when common end-product specifications are used.

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