1-1-2014

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Recommended Citation

Heitor, Ana; Indraratna, Buddhima; and Rujikiatkamjorn, Cholachat, "Aspects related to the small strain shear modulus behaviour of compacted soils subjected to wetting and drying" (2014). *Faculty of Engineering and Information Sciences - Papers: Part A*. 2159.
https://ro.uow.edu.au/eispapers/2159

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Abstract

The dynamic properties of a soil are routinely investigated to describe its engineering behavior under repeated loading. Although the effect of suction on the dynamic response of soils is significant, there have been limited studies in which the post-compacted changes in suction induced by wetting and drying cycles have been considered. In this paper, aspects related to the dynamic properties with special reference to the small strain shear modulus of compacted soils subjected to wetting and drying are described. Further evidence on the dynamic response in terms of small strain shear modulus (G0) of a compacted soil subjected to wetting-drying is presented and novel insights into small strain behavior in multiple cycles of wetting and drying are shown. Particular emphasis is placed on the hysteric behavior and its dependence on the suction history. The results not only confirm the importance of the current suction ratio (or CSR), but also suggest that subsequent wetting-drying cycles further induce hysteretic changes in relation to the small strain shear modulus, particularly when following the wetting paths.

Keywords

related, aspects, subjected, soils, drying, compacted, wetting, behaviour, modulus, shear, strain, small

Disciplines

Engineering | Science and Technology Studies

Publication Details

Heitor, A., Indraratna, B. & Rujikiatkamjorn, C. (2014). Aspects related to the small strain shear modulus behaviour of compacted soils subjected to wetting and drying. Geo-congress Technical Papers: Geo-characterization and Modelling for Sustainability (pp. 1433-1442). United States: American Society of Civil Engineers.

Aspects related to the small strain shear modulus behaviour of compacted soils subjected to wetting and drying

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ABSTRACT: The dynamic properties of a soil are routinely investigated to describe its engineering behaviour under repeated loading. Although the effect of suction on the dynamic response of soils is significant, there have been limited studies in which the post-compacted changes in suction induced by wetting and drying cycles have been considered. In this paper aspects related to the dynamic properties with special reference to the small strain shear modulus of compacted soils subjected to wetting and drying are described. Further evidence on the dynamic response in terms of small strain shear modulus (G_0) of a compacted soil subjected to wetting-drying is presented and novel insights into small strain behavior in multiple cycles of wetting and drying are shown. Particular emphasis is placed on the hysteric behavior and its dependence on the suction history. The results not only confirm the importance of the current suction ratio (or CSR) but also suggest that subsequent wetting-drying cycles further induce hysteretic changes in relation to the small strain shear modulus, particularly when following the wetting paths.

INTRODUCTION

The dynamic properties of the soil such as the small strain shear modulus are usually evaluated to characterize the engineering behavior of earth structures subjected to repeated loading (i.e. vibrations caused by traffic of heavy and fast moving vehicles, heavy earthwork machinery, and earthquakes).

The results from previous research studies indicate that the small strain modulus is dependent on the level of stress, the as-compacted water content and changes in post-compaction suction (Claria and Rinaldi, 2004; Sawangsuriya et al., 2008, Heitor et al., 2012). In fact, the small strain stiffness was found to be associated with the of soil water retention characteristics, in particular related to the different ranges observed in the soil water retention curve or SWRC (i.e. Cho and Santamarina, 2001 and Mancuso et al. 2002). Cho and Santamarina (2001) reported an increase in the shear wave velocity in the transition from funicular to pendular states, where the development of water menisci at the particle contacts would contribute to a considerable increase in the stiffness of the soil skeleton. Furthermore, Mancuso et al. (2002) investigated the effect of suction on the small strain shear modulus in the low suction range and found that the shear modulus increased with suction, however, a noted inflexion was observed at air entry value (AEV) and two distinct ranges were defined, a bulk water regulated zone and a menisci water regulated zone. Before AEV the shear modulus increases linearly with suction, thereafter its increase is predominantly non-linear. Similar observations were also reported for a range of different soils by Marinho et al. (1996); Vinale et al. (2001), Inci et al. (2003), Sawangsuriya et al. (2008) and Heitor et al. (2013). Mancuso et al. (2002) also revealed that the small strain shear modulus is affected by the soil fabric derived from the compaction process. It is interesting to note that although the tendency is similar, the transition points (i.e. air entry value or AEV) are consistent with the behaviour that might be expected from the SWRC of specimens prepared in such conditions. These observations are also in accordance with effect of inherent double porosity differences associated to compacted soils prepared at OMC and wet of OMC, particularly evident in the small strain shear modulus rate of increase with suction. Also, the data presented in Mancuso et al. (2002) seems to suggest that the small strain shear modulus is more sensitive to changes in suction when the SWRC is within the macroporosity range, remaining nearly constant in once the residual water content is exceed (also interpreted as the beginning of microporosity range, see i.e. Romero et al. 1999).

While during their service live most earth structures experience changes in hydraulic behaviour owing to the climatic changes (i.e. rainfall or extended periods of drought), limited studies have evaluated its impact on the small strain shear modulus. These seasonal cyclic fluctuations induced by cycles of wetting and drying have in turn substantial effects on the soil geomechanical performance in relation to its dynamic response.

Ng et al. (2009) and Ng and Xu (2012) investigated the effect of a drying-wetting cycle at a constant mean net stress on the small strain stiffness of an unsaturated completely decomposed tuff. The most striking aspect was that alike the SWRC the small strain stiffness also showed hysteresis between the drying and wetting paths, albeit the size of the loop was small. Furthermore, it was reported that at any given suction level, the shear modulus of the wetting path was higher than the corresponding on the drying path. This is owing to the amount of water in the soil, as reflected by the degree of saturation (S_r), which represents the cumulative number of air-water menisci affecting inter-particle connections for a given suction level. Thus, despite having the same suction, upon drying and wetting, the different amounts of water in the soil lead to different mechanical behavior, for instance related to the elasto-plastic hardening mechanisms. Similar observations were also reported for silt (Khosravi and McCartney, 2012) and sand mixes (George, 2009).

The shear modulus data can also be analyzed in terms of the current suction ratio or CSR which reflects the suction history the soil has been exposed to. The small strain shear modulus was reported to increase by about 20% when the CSR increased from 1 to 2 (Ng and Xu, 2012).

This paper aims to offer further evidence on the dynamic response in terms of small strain shear modulus (G_0) of a compacted soil subjected to wetting-drying and offers novel insights into small strain behavior in multiple cycles of wetting and drying. The salient aspects in relation to the hysteresis loop and the change CSR for additional cycles of wetting and drying are also addressed.

EXPERIMENTAL WORK

The soil used in this study was a 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 (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.

The testing program consisted of carrying out wetting and drying tests on a compacted soil specimen. Compacted samples were obtained by using a ∅50×100mm mould. The compaction energy was adjusted so that the dry unit weight would correspond to the Proctor compaction (AS1289.5.1.1-2003). For illustration of the compaction behavior of the material, the results obtained for other energy levels are plotted together with equivalent standard compaction effort corresponding to E_3=529.50kJ/m^3 in Fig. 1(a). As-compacted suction was also routinely measured using filter paper method (ASTM D5298, 2003) and a small tip tensiometer (ASTM D3404-91, 2004) and the obtained results are shown in Fig. 1(b). Although there is no apparent relationship between suction and compaction energy, all data points seem to converge to a logarithmic regression line which indicates that as-compacted suction may be relatively independent of the compaction characteristics (i.e. change in the water content and energy level).

For the wetting and drying tests a specimen prepared at optimum moisture content and dry unit weight equivalent to standard Proctor effort was chosen. The specimen was tested using bender elements under isotropic confined conditions for different levels of suction. An isotropic confining pressure of 50kPa (equivalent to approximately 2.5m depth) was adopted because it is considered to be a conservative lower bound of the depth where soil is likely to be subjected to wetting and drying cycles from climatic changes in Penrith. The adoption of this value was largely based on the Thornthwaite moisture index (TMI) distribution in Australian territories (Austroads, 2004; Fityus and Buzzi, 2008).

Suction was imposed to the specimens by applying axis translation technique to attain the desired pressure differential or suction. The air and water pressures, applied to the specimen in a load frame triaxial cell, were controlled with pressure controllers designed by GDS Instruments (accuracy of 1mm^3) and the high air entry value (AEV) ceramic disk embedded on the bottom pedestal had an AEV of 15 bar. The water pressure controller was able to measure the volume of water flowing in or out of the specimen when the suction was changed. The criterion for equilibrium was based on the change in the volume of water (Fig. 2). The equilibrium as assumed to be reached if the volume of water exchange in a period 6h was less than 5mm^3. In these tests, the increments in each stage were 50kPa and the water pressure was changed at a rate of

0.16kPa/min and kept constant until the end of the equilibration period. Typically, periods of 48 to 72h were sufficient for the specimens to reach equilibrium. The axial displacement was also monitored at every stage using an LVDT (Linear Variable Differential Transducer) with an accuracy of 0.001mm. Any changes in the axial strain associated with drying and wetting of the specimens were very small, typically less than 0.01%.

The SWRC of a specimen prepared at the same water content and energy level was monitored for a net confining stress of 50kPa. The procedure adopted for applying suction increments was similar to that of the wetting and drying tests, however, prior to applying the first suction increment, the specimen was saturated. Similarly, for every suction stage, the equilibration period was usually 48h.

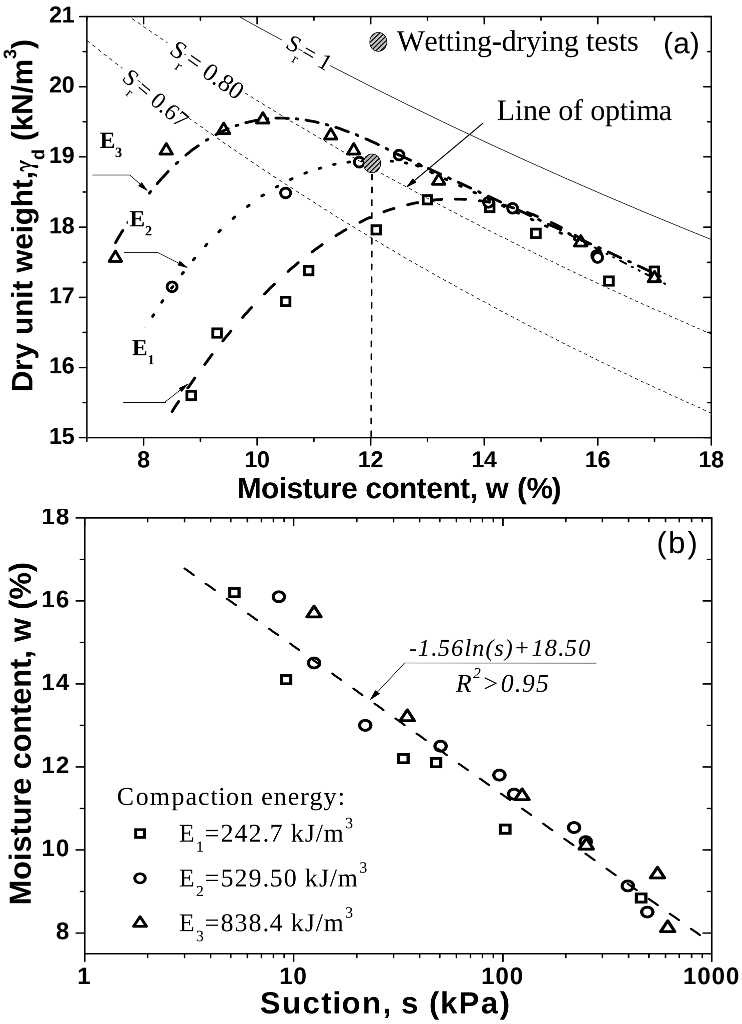

FIG. 1. Compaction data for the silty sand soil (a) compaction curves and (b) as-compacted suction (modified after Heitor et al. 2013).

A pair of bender elements assembled in a bottom pedestal and top cap was used to monitor the shear waves transmitted through the specimens. The bender elements signal generation was controlled by GDSBES v2.0 software (GDS Instruments) while the data acquisition system had two input channels with 16-bit resolution each. A sampling rate of 300 kHz was used to ensure an adequate resolution of the time and voltage of input and output signals (Clayton, 2011). In order to minimize background noise and improve the signal to noise ratio (SNR), a series of twenty sampled signals were stacked. In this study, it was found that a testing frequencies having a ratio between wave path length (L_{tt}) and wavelength (λ) exceeding 2 (Arulnathan et al., 1998; Leong et al., 2005) were adequate to minimize the effect of the near-field component effect and warrant the strength of the received signal. The shear wave velocity (V_s) and small strain shear modulus (G_0) were computed based on the wave path length (L_{tt}), the travel time (Δt) and bulk unit weight (γ), as follows:

$$V_s = \frac{L_{tt}}{\Delta t} \tag{1}$$

$$G_0 = \frac{\gamma}{g} V_s^2 \tag{2}$$

where g = gravity constant.

The travel time (Δt) was taken as the time interval to the first bump maximum, as described by Lee and Santamarina (2005) or to the first deflection if the first bump was not visible.

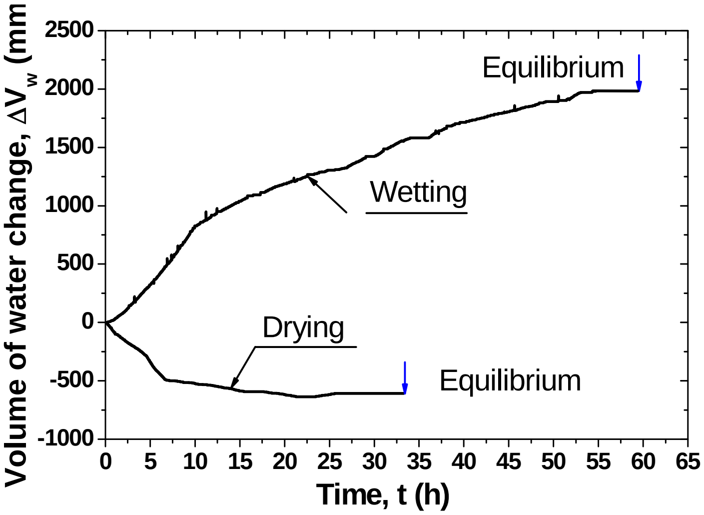

FIG. 2. Volume of water change during wetting and drying (after Heitor, 2013)

RESULTS AND DISCUSSION

A specimen representative of the standard compaction energy prepared at optimum water content was tested with bender elements for different levels of suction in two cycles of wetting and drying. The variation of G_0 with increasing (drying) and decreasing (wetting) suction is depicted in Fig. 3 (a). The most striking aspect is that G_0 exhibits higher values when following the wetting paths. This might not correspond to the expected intuitive behaviour at first glance, but it can be associated with the soil-water exchange in soil pores, responsible for the hysteretic response observed in the SWRC represented in Fig. 4 (i.e. the ink-bottle effect). In addition, microstructural studies (i.e. Cuisinier and Laloui, 2004; Monroy et al., 2010) have shown that the soil fabric is also evolving into a more constricted porosity centered at the microporosity range when the soil dries, and partly recovering some of the macroporosity when it is wetted. Note that this change in fabric refers only to changes in soil structure occurring when the soil specimens are wetted or dried. These results are also consistent with the studies on decomposed tuff and Bonny silt conducted by Ng and Xu (2012) and Khosravi and McCartney, (2012), respectively.

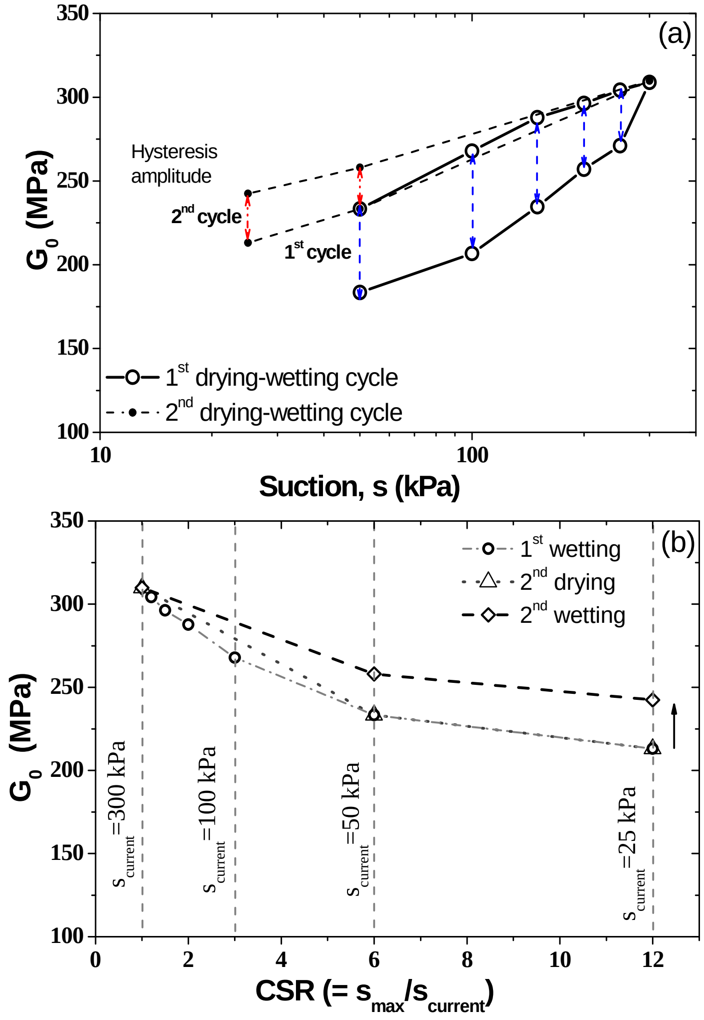

FIG. 3. Small strain shear modulus during wetting and drying in terms of (a) suction and (b) CSR..

Further inspection of Fig. 3 reveals another important point; while the G_0 value is recovered when the soil is subjected to a second cycle of drying at a suction of 300kPa, in the subsequent wetting cycle G_0 displays again hysteretic behaviour and shows an increase of 24.7MPa. G_0 would be expected to show slight hysteresis on both paths, similar to the SWRC response (Fig. 4a), but this is not the case. A possible explanation may lie within the changes in the soil structure that take place as a result of the wetting and drying processes. In fact, Koliji et al. (2010) reported that in a high suction range the volume of aggregations are reversible, whereas in low suction the wetting path shows fewer aggregations.

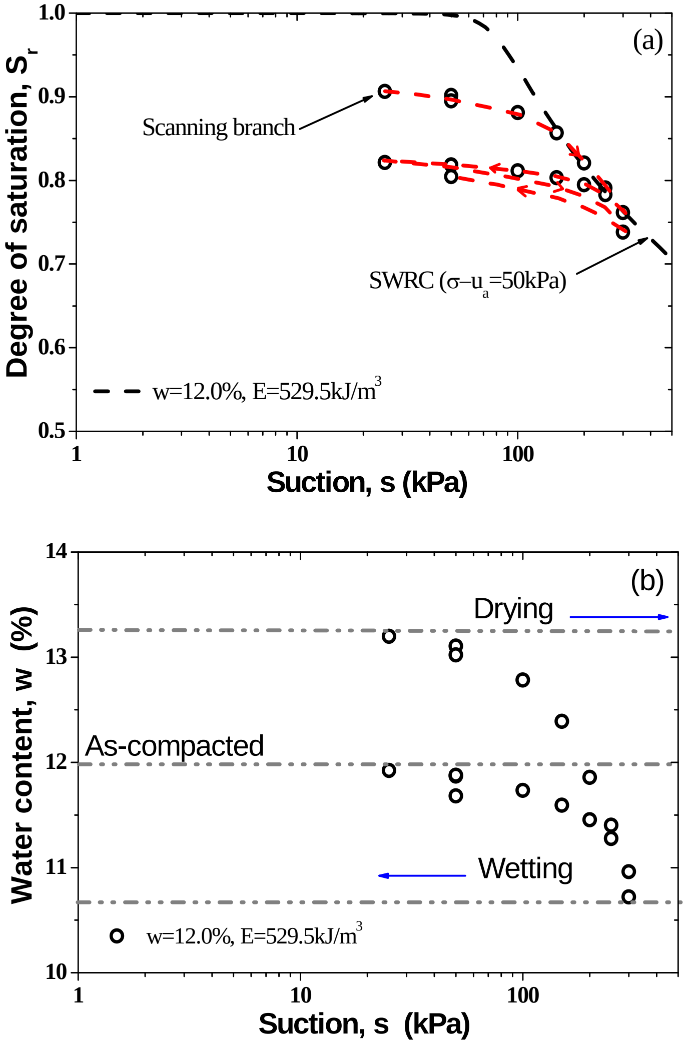

FIG. 4. Water retention data of the drying-wetting cycles in terms of (a) degree of saturation and (b) water content.

Ng and Xu (2012) referred to the current suction ratio or CSR (Eq. 3), in governing the small strain stiffness and mechanical response at small strain.

$$CSR = \frac{s_{\max}}{s_{current}} \tag{3}$$

where s_{max} = is the maximum suction the specimen has been exposed to and $s_{current}$ = current suction level.

In Fig. 3b the G_0 values are plotted against the CSR values computed for the wetting paths. The results suggest that not only is the CSR important, so too are the number of cycles of wetting-drying, since at a suction of 50kPa, a CSR of 6 was obtained for both the first and second wetting cycles, and yet G_0 differs by 24.7MPa. Note that the CSR values for the first drying path are not represented because in the first drying the highest suction the specimens were exposed to correspond to the testing suction and thus CSR was 1 along the first drying path.

Fig. 4 shows the corresponding water retention data computed based on the volume of water at the end of the equilibrium stages. A marked hysteresis was observed between the wetting and drying paths (Fig. 4a). The second cycle of drying further induced some hysteretic behavior but in a much smaller amount in comparison with the 1st cycle. This indicates that the hysteresis amplitude is progressively decreasing for an increasing number of drying and wetting cycles. In addition, while the 'ink bottle' effect is likely still present, its importance may have been reduced, which in turn indicates that the soil is experiencing irrecoverable structural changes and the pore size distribution is becoming more uniform. This behavior is also consistent with the observations made for a range of different soils (i.e. Pham et al. 2005; Colmenares, 2002).

The SWRC of a specimen equivalent to the one tested in the drying and wetting cycles obtained for the same stress conditions (i.e. net stress of $(\sigma_a\text{-}u_a)$=50kPa) is also shown as a reference.

Fig 4a) also shows that for the suction range between 25 to 150kPa the specimen was mainly lying on the scanning curves. In practice the soil may not always follows a continuous path from a totally dried or wetted state similarly to what would be expected in the SWRC determination. In most cases the soil is likely to be at an intermediate stage of saturation described by the scanning curves and thus equivalent to field conditions.

The water retention data is also replotted in terms of water content (Fig. 4b). The equivalent changes of water content in range of suction selected resulted in variations of ±1.5%. This indicates that even a small change in water content in the field may lead to considerably different values of G_0.

CONCLUSIONS

From a number of bender element tests conducted in a compacted specimen subjected to post-compaction cycles of wetting and drying it was observed that the effect of suction variation on small strain stiffness is significant. Larger values of G_0 correspond to the wetting paths and this difference was related to the water retention and associated mechanical properties. Subsequent cycles of drying-wetting continue to further induce changes in G_0 , that may be associated with fabric changes occurring during the drying-wetting. G_0 exhibited hysteretic response alike the SWRC but the amplitude decreased in the subsequent cycles. The CSR appears to control the G_0 to some extent but subsequent wetting-drying cycles induce further hysteretic changes that contribute to an added increase in G_0 for the same CSR. Finally, this study shows that the geomechanical behaviour of earth structures exposed to changes in hydraulic regimes is dynamic and should be considered when evaluating long term performance.

ACKNOWLEDGMENT

The assistance provided by the Australia Research Council, Penrith Lakes Development Corporation, Coffey Geotechnics and Mr. Alan Grant is gratefully acknowledged.

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