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Role of the compaction energy level on the small strain stiffness of a silty sand soil subjected to wetting and drying

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Abstract

The dynamic properties of a soil are routinely quantified to describe its engineering behaviour under repeated loading. While the results of previous research studies indicate that the effect of changes in suction on the dynamic response is significant, only limited research has been engaged in the assessment of post-compacted changes in suction induced by cycles of wetting and drying. In this paper, aspects related to the dynamic properties with special reference to small strain shear modulus behaviour at different compaction energy levels are described and outlined. Particular emphasis is placed on the hysteric behaviour observed (i.e. amplitude of the hysteresis loop) and its dependence on the imparted compaction energy. The results not only confirm the importance of the recent suction ratio (or CSR) in governing the mechanical response at small strain, but they also indicate that higher compaction energy levels induce smaller hysteresis loops.

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Role of the compaction energy level on the small strain stiffness of a silty sand soil subjected to wetting and drying

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ABSTRACT: The dynamic properties of a soil are routinely quantified to describe its engineering behaviour under repeated loading. While the results of previous research studies indicate that the effect of changes in suction on the dynamic response is significant, only limited research has been engaged in the assessment of post-compacted changes in suction induced by cycles of wetting and drying. In this paper, aspects related to the dynamic properties with special reference to small strain shear modulus behaviour at different compaction energy levels are described and outlined. Particular emphasis is placed on the hysteric behaviour observed (i.e. amplitude of the hysteresis loop) and its dependence on the imparted compaction energy. The results not only confirm the importance of the recent suction ratio (or CSR) in governing the mechanical response at small strain, but they also indicate that higher compaction energy levels induce smaller hysteresis loops.

1 INTRODUCTION

The dynamic properties of 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). Indeed, 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 the 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), and Sawangsuriya et al. (2008), 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. Although, the results showed similar trends for specimens prepared at optimum moisture content (OMC) and wet of OMC, the transition points (i.e. AEV) were in accordance with the soil water reten-

tion curve (SWRC) behavior. These observations are also consistent with effect of inherent double porosity differences associated with compacted soils prepared at OMC and wet of OMC, particularly evident in the small strain shear modulus rate of increase with suction. Furthermore, 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 once the residual water content is exceeded (also interpreted as the beginning of microporosity range).

While during their service life 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, particularly in relation to its dynamic response.

Ng et al. (2009) and Ng and Xu (2012) investigated the effect of a drying-wetting cycle on the small strain stiffness of an unsaturated completely decomposed tuff. The most striking aspect was that like the SWRC, the small strain stiffness also showed hysteresis between the drying and wetting paths, albeit the size of the loop was small. Furthermore, for any given suction level, the shear modulus of the wetting path was higher than on the drying path. Similar observations were also reported for silt (Khosravi, 2012) and sand mixes (George, 2009). The small

strain shear modulus data can also be analyzed in terms of the current suction ratio or CSR ($CSR = s_{max}/s_{current}$; s_{max} = maximum suction experienced and $s_{current}$ = current suction level). In fact, Ng et al. (2012) study showed a small strain shear modulus increase of about 20% when the CSR increased from 1 to 2.

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 cycles of wetting and drying for different compaction energy levels. The salient aspects in relation to the hysteresis loop and the change in CSR for the cycle of wetting and drying are also addressed.

2 EXPERIMENTAL WORK

2.1 Soil type and compaction characteristics

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 compacted soil specimens. Compacted samples were obtained by using a $\varnothing 50 \times 100$mm 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 two additional energy levels are plotted together with equivalent standard compaction effort corresponding to $E_2 = 529.50$kJ/m³ 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).

2.2 Wetting and drying tests

For the wetting and drying tests three specimens prepared at water content of 0.12 and different ener-

gy levels corresponding to 245.7, 529.5 and 838.4kJ/m³ were selected (Fig. 1). The specimens were 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 (H_s) from climatic changes in Penrith (Fig. 2). The adoption of this value was largely based on the Thornthwaite moisture index (TMI) distribution in Australian territories (Austroads, 2004; Fityus and Buzzi, 2008).
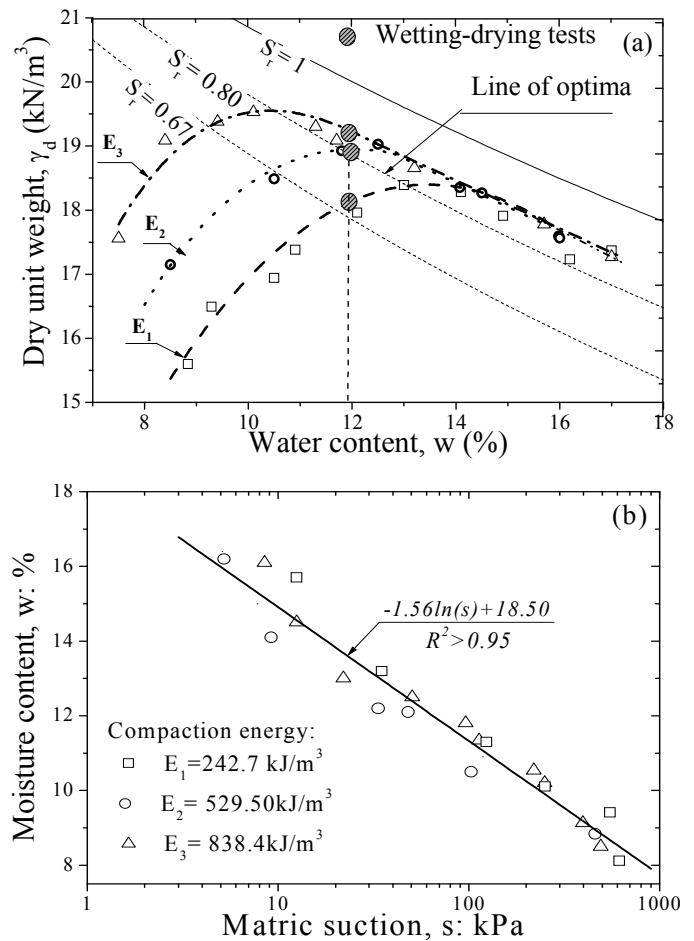

Figure 1. Compaction data for the silty sand soil (a) compaction curves and (b) as-compacted suction (modified after Heitor et al. 2013).
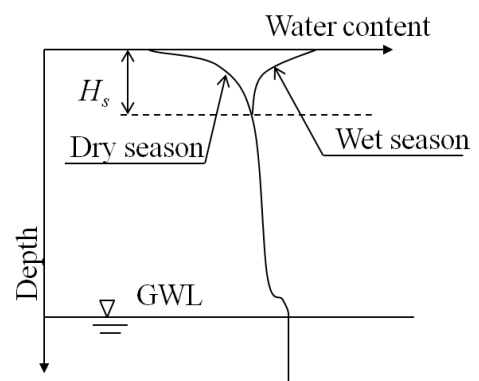

Figure 2. A profile of the ground water content exposed to seasonal climatic variations (Heitor, 2013).

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 specimens when the suction was changed. The criterion for equilibrium was based on the change in the volume of water (Fig. 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 48h 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%.
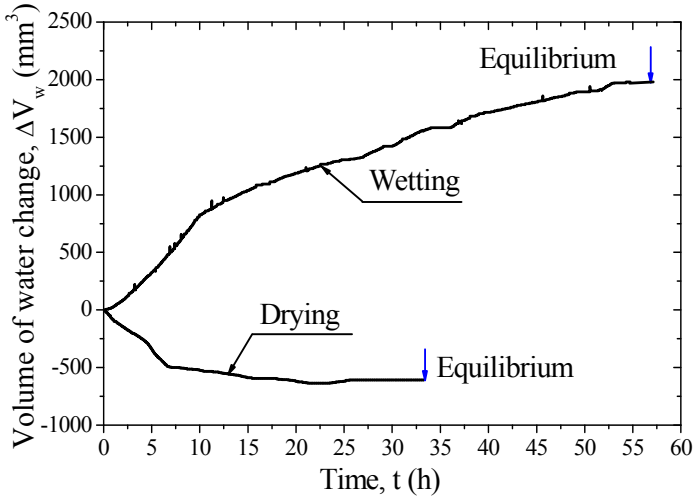

Figure 3. Volume of water change during wetting and drying.

2.3 *Small strain shear modulus*

A pair of bender elements assembled in a bottom pedestal and top cap was used to monitor the shear waves transmitted through the specimens (Fig. 4). 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 testing frequencies (varying from 1.4 to 50kHz) 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 near-field component effect and warrant the strength of the received signal (Fig. 5). 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.
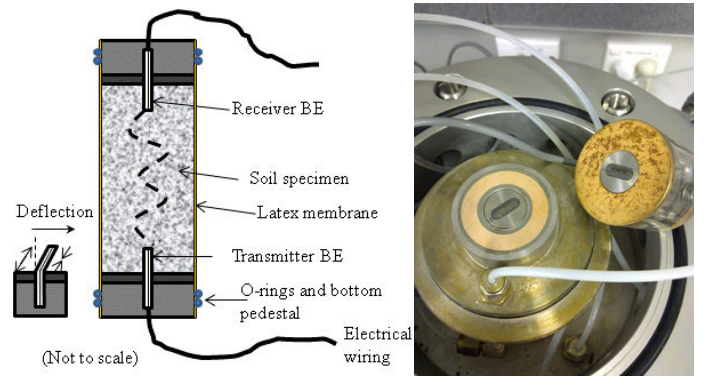

Figure 4. Illustration of a pair of BE (left) and detail of the bender elements cantilevered in the AEV ceramic bottom pedestal and top cap (right).
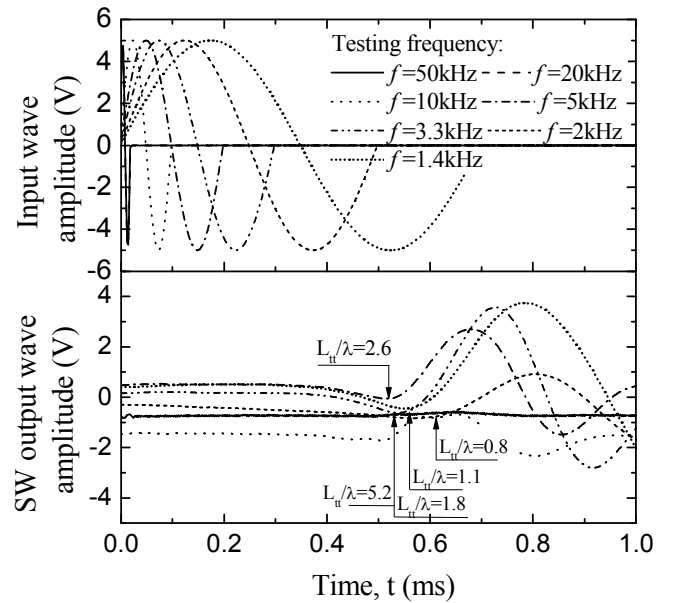

Figure 5. Typical shear wave velocity traces for different testing frequencies varying from 1.4 to 50kHz.

3 RESULTS AND DISCUSSION

3.1 *Small strain shear modulus*

Three specimens prepared at 12% water content and compaction energy levels of 252.7, 529.50 and 838.4 kJ/m^3 were tested with bender elements for different levels of suction in one cycle of wetting and drying. The variation of G_0 with increasing (drying) and decreasing (wetting) suction is depicted in Fig. 6. The most striking aspect is that G_0 exhibits higher values when following the wetting paths for all three specimens. 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 and hydraulic loading history. In fact, this behavior can also be related to the hysteretic response observed in the SWRC represented in Fig. 8 (i.e. the ink-bottle effect). In addition, microstructural studies (i.e. Cuisinier and Laloui, 2004, Monroy et al., 2010) have reported that when the soil is drying, the fabric is also evolving into a more constricted porosity centered at the microporosity range, and partly recovers some of the macroporosity when it is wetted. Note that this change in fabric refers to changes in soil structure occurring when the soil is subjected to drying and wetting processes.

The results represented in Fig. 6 also show that G_0 extent of the hysteretic response seems to be associated with the initial compaction energy level, which in turn is associated with the initial compacted dry unit weight and soil structure. Heitor et al. (2013) showed that the soil macrostructure evolves gradually from an aggregated type of structure to a matrix type of structure with the increase of compaction energy. This difference in the initial soil macrostructure together with the dry unit weight is likely the cause for the difference in the hysteresis amplitude. Indeed, the specimen prepared at an energy level of 242.7kJ/m^3 has the highest hysteresis amplitude of 85MPa, followed by the specimen prepared at energy level of 529.5kJ/m^3 with 45MPa and by the specimen prepared at energy of 838.7kJ/m^3 with 16MPa (Fig 5). Interestingly, the specimen prepared at the 242.7kJ/m^3 that has a corresponding maximum dry unit weight ratio of 93%, which is just slightly below the common end-production specification of 95% (AS 3798 − 2007) shows an hysteresis amplitude nearly double compared to the specimen prepared at equivalent Standard Proctor. This seems to indicate that even slight changes in the field energy level have an important impact on the post-compacted dynamic response of the compacted fills.

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

$$CSR = \frac{s_{max}}{s_{current}} \qquad (3)$$

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

In Fig. 7 the G_0 values normalized by the current suction are plotted against the CSR values computed for the wetting paths. As expected the specimens compacted with a higher energy level yield the larger G_0 values for any given CSR but the difference is much smaller for energy levels of 529.5kJ/m^3 and 838.4 kJ/m^3. Note that the CSR values for the drying paths are not represented because in the first drying the highest suction the specimens were experienced corresponded to the testing suction and thus CSR was 1 along the drying paths.
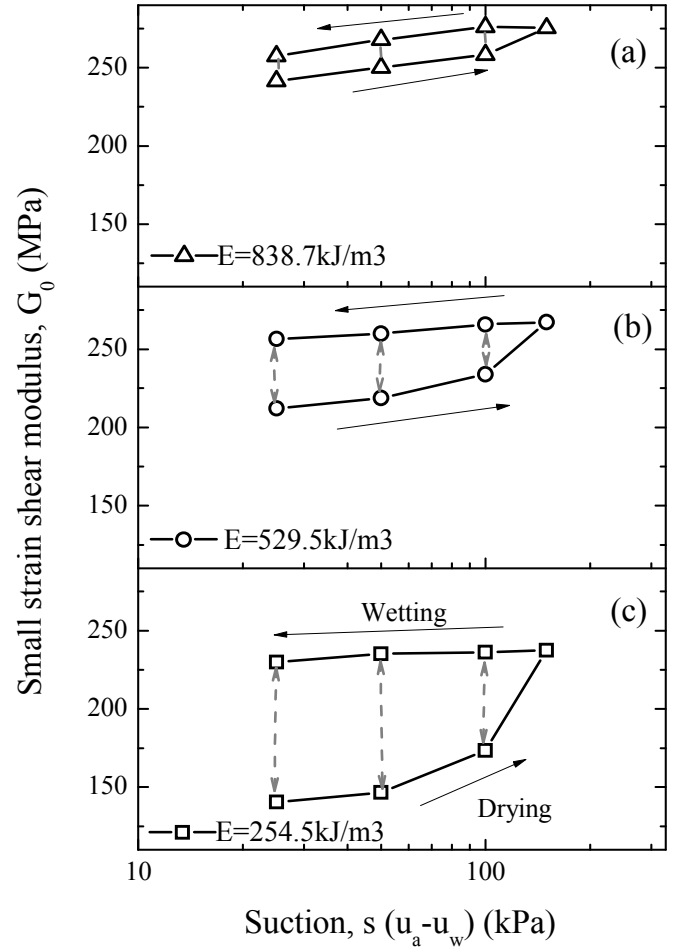

Figure 6. G_0 during wetting and drying for specimens compacted at energy levels of (a) 838.4 kJ/m^3, (b) 529.5kJ/m^3 and (c) 242.7 kJ/m^3.

3.2 *Water retention*

Fig. 8 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. 8). Like the small strain shear modulus, the hysteresis seemed to be dependent on the initial soil structure and dry unit weight of the specimens prepared at different energy levels.
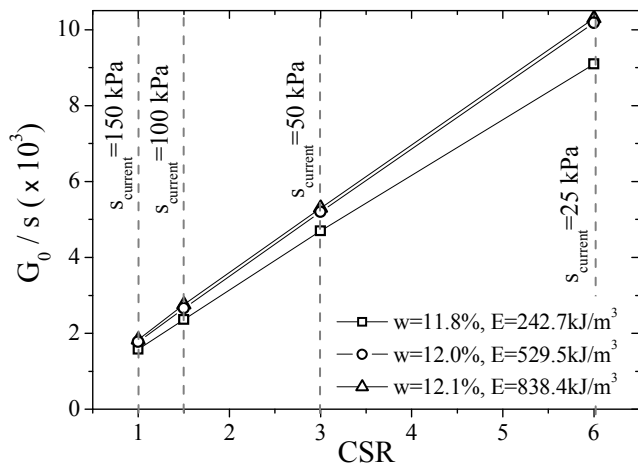
Figure 7. G_0 / s ratio with CSR for the wetting paths of specimens compacted at energy levels of 242.7, 529.5kJ/m^3 and 838.4 kJ/m^3.

The SWRC for a specimen prepared at the energy level equivalent to Standard Proctor is also shown as a reference. Notice that for all the suction levels considered, the specimens were mainly lying on the scanning curves, which is predominantly equivalent to the field condition. The equivalent changes in suction resulted in variations in the water content of only ±1.0%, which indicates that even a small change in moisture content in the field may lead to considerably different values of G_0.
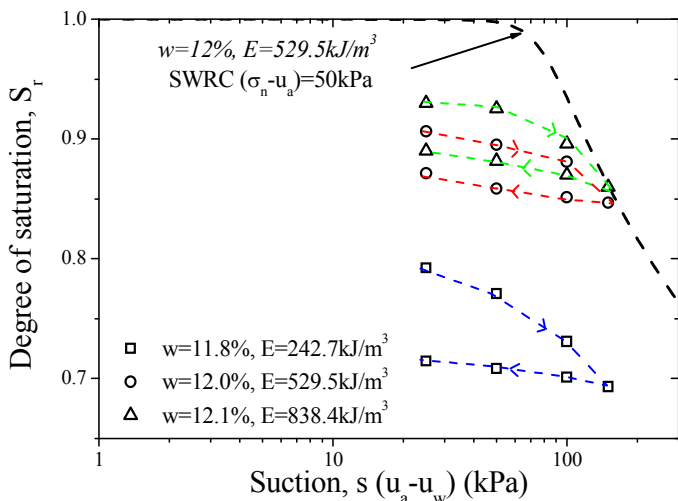

Figure 8. Water retention data of the drying-wetting cycles in terms of degree of saturation.

4 CONCLUSIONS

From a number of Bender element tests conducted in specimens compacted at three different energy levels and then subjected to a post-compaction cycle 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 associated with the water retention properties. The initial dry unit weight and associated soil structure that results from preparing the specimens at different energy levels has a

strong influence on the amplitude of the hysteretic response observed in a cycle of wetting and drying. Larger hysteresis amplitudes were observed for specimens compacted at lower energy levels. This indicates that poorly compacted conditions result in relatively large changes in the post-compacted mechanical response of materials. Furthermore, the CSR appears to control the G_0 to some extent but the energy level contributes to an 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 particularly for cases where the fills may have been inadequately compacted.

5 ACKNOWLEDGMENT

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