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Abstract

Conventional field compaction control methods are effective at the time of placement. However, the discrete nature of these measurements and a limited depth of investigation can render them unsuitable for post-construction compaction quality assessments of deeper fills or larger surface areas. In this situation, classical destructive geotechnical surveys (i.e. boreholes, cone penetration tests) are sought to evaluate the current fill conditions. Nevertheless, these methods often do not provide the required level of information because only certain locations are tested and they have tremendous implications in terms of cost. The use of available non-destructive methodologies, such as shear wave velocity surveys (i.e. SASW, spectral analysis of surface waves or HVSr, horizontal-to-vertical spectral ratio) together with electrical resistivity tomography surveys (e.g. evaluation of water content), offers a valuable alternative to efficiently control compaction over large areas during post-construction stages and locate areas within the existing formations where the soil was not sufficiently compacted. This study explores the performance of a cost effective method for evaluating the characteristics of compacted fills by measuring the shear wave velocity and matric suction to evaluate the void ratio or dry density of compacted soil. Laboratory studies of compacted specimens were used to evaluate this method and their performance under different isotropic confining pressures. The results showed that the shear wave velocity and matric suction can effectively predict how the soil is compacted, but its success requires field measurements of both shear wave velocity and matric suction. The application of this relationship would enable practitioners to efficiently control compaction over large areas during post-construction stages, and locate areas within the existing formations where the soil was not sufficiently compacted.

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ASSESSMENT OF THE POST-COMPACTION CHARACTERISTICS OF A SILTY SAND

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ABSTRACT

Conventional field compaction control methods are effective at the time of placement. However, the discrete nature of these measurements and a limited depth of investigation can render them unsuitable for post-construction compaction quality assessments of deeper fills or larger surface areas. In this situation, classical destructive geotechnical surveys (i.e. boreholes, cone penetration tests) are sought to evaluate the current fill conditions. Nevertheless, these methods often do not provide the level of required information because only certain locations are tested and they have tremendous implications in terms of cost. The use of available non-destructive methodologies, such as shear wave velocity surveys (i.e. SASW, spectral analysis of surface waves or HVSr, horizontal-to-vertical spectral ratio) together with electrical resistivity tomography surveys (e.g. evaluation of water content), offers a valuable alternative to efficiently control compaction over large areas during post-construction stages, and locate areas within the existing formations where the soil was not sufficiently compacted.

This study explores the performance of a cost effective method for evaluating the characteristics compacted fills by measuring the shear wave velocity and matric suction to evaluate the void ratio or dry density of compacted soil. Laboratory studies of compacted specimens were used to evaluate this method and their performance under different isotropic confining pressures. The results showed that the shear wave velocity and matric suction can effectively predict how the soil is compacted, but its success requires field measurements of both shear wave velocity and matric suction. The application of this relationship would enable practitioners to efficiently control compaction over large areas during post-construction stages, and locate areas within the existing formations where the soil was not sufficiently compacted.

Keywords: compaction control, shear wave velocity, matric suction

1 INTRODUCTION

Compaction has been widely used in civil works to improve the geotechnical and geomechanical characteristics of soil. The inauspicious circumstances of some accidents, whether they were related to poor compaction or a lack of understanding of the compaction process, have resulted in an intensive study of compacted materials. Several researchers (e.g. Seed and Chan, 1959, Turnbull and Foster, 1956, Olson and Langfelder, 1965) have identified the structure, stress-deformation characteristics, shear strength, development of pore pressure, and the effective strength characteristics of compacted soil along the compaction curve. Despite these major achievements, the effect that changes in the structure of soil caused by compaction on the mechanical and hydraulic behaviour, especially under unsaturated conditions, is still not well understood. This aspect is of particular importance in terms of quality control because the common end product specifications (AS 3798 - 2007) do not stipulate the compaction paths, only the final target conditions in relation to water content and dry unit weight.

Conventional methods for controlling compaction in the field, including e.g. nuclear gauge and sand cone, are adequate for controlling the compacted soil at the time of placement, yet because of their localised nature, these techniques may not be suitable for deeper fills or for assessing larger areas. This is particularly important in the detection of soft spots that may lead to problems related to insufficient

bearing capacity during the service life of the fill. Thus, under these conditions, alternative non-destructive methods based on the shear wave velocity propagation should be considered. Shear wave velocity (V_s) surveys; have been used extensively in many geotechnical applications to evaluate the dynamic properties of ground. The shear wave, which propagates through the soil skeleton, is an adequate variable to verify the quality of compaction during construction. However, its direct application for assessing the current state of compacted fills (post-construction stages) is not straightforward because compacted soil is under unsaturated condition and the in situ suction plays an important role in controlling the shear wave velocity and associated small strain stiffness. Indeed, recent studies on the propagation of shear waves in compacted soils showed that a variation of suction influences the stiffness of the soil skeleton, which in turn affects the shear wave velocity or small strain shear modulus (e.g. Cho and Santamarina, 2001; Mancuso et al., 2002; Indraratna et al., 2012; Rujikiatkamjorn et al., 2012, Heitor et al, 2014a). While the theoretical concepts and fundamental basis of the propagation of shear wave and suction have been well established individually and separately, only a limited number of studies have focused on the propagation of shear waves in soils compacted under different conditions (water content and energy). In this study, a new methodology is proposed to assess the quality of compaction in post-construction stages and older compacted embankments where few or no records of the method of control at the time of construction are available. This methodology is based on propagation of the shear wave for different compaction states while considering unsaturated conditions.

2 TESTING PROGRAM

2.1 - SPECIMEN PREPARATION

A silty sand soil, classified as SP-SM was used in this study. The soil is a by-product of cobble quarrying activities that has been widely used to fill low-lying areas at the Penrith Lakes (NSW, Australia). While the soils 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 had a liquid limit of 25.5%, a plasticity index of 10 and specific gravity of 2.7.

The compaction characteristics were established for different energy level using standard Proctor compaction mould (AS1289.5.1.1-2003). The specimens prepared for subsequent testing were compacted in a 50 mm diameter and 100 mm height mould following the procedure described in Heitor et al. (2012). The specific compaction energy used in the $\varnothing 50 \times 100$ mm mould was adjusted to meet the standard Proctor mould dry unit weight values (Figure 1a). A total of 25 specimens were prepared at various water contents and energy levels and tested under unconfined conditions and 15 specimens were tested under isotropic confinement. Additional specimens were also prepared to check the test repeatability and evaluate the impact of near-surface moisture changes via wetting and drying.

2.2 MATRIC SUCTION

Matric suction was measured using the filter paper method (Whatman No.42) and a small-tip tensiometer (Soil Moisture Equipment Corp.) in accordance with ASTM D5298 (2003) and ASTM Standard D3404-91 (1998), respectively. Figure 1b shows the water retention data for specimens compacted at different energy levels. The suction values varied from 616 kPa on the dry side of the OMC (highest compaction effort) to 5 kPa on the wet side of the OMC (lowest compaction effort). In these tests, the amount of suction developed by compaction was not very high because the clay fraction in the tested soil was very small ($< 12\%$). Overall, the suction decreases with an increasing water content. 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) ($R^2 > 0.95$). This suggests that the moisture content influencing on suction is more important than the compaction energy and the field suction can be estimated once the moisture content is known.

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

For wetting and drying tests, suction was controlled using axis translation technique. The air and water pressures (u_a and u_w respectively) were controlled with pressure controllers designed by GDS Instruments (accuracy of 1mm^3) and the high air entry value (AEV) of 15 bar ceramic disk was embedded on the bottom pedestal (Figure 2). The suction increment in each stage was 50kPa and the water pressure was changed at a rate of 0.16kPa/min until the end of the equilibration period. The volume of water flowing in or out of the specimens was monitored during the equilibration period. Typically, periods of 48h were sufficient for the specimens to reach equilibrium.

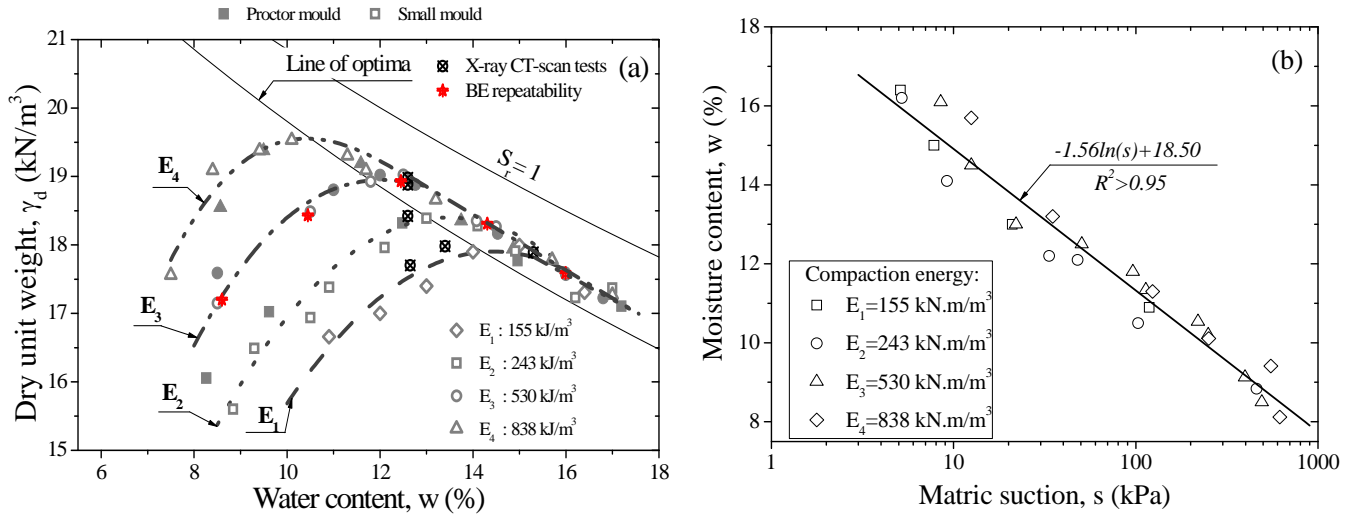


Figure 1– Compaction data for the silty sand soil: (a) compaction plane and (b) water retention (modified after Heitor et al. 2013).

2.2- SHEAR WAVE VELOCITY

The shear wave velocity was determined using Bender elements adapted in the standard triaxial cell apparatus (Figure 2). The signal generation was controlled by software designed by GDS Instruments (UK) and the data acquisition system had 2 input channels, with 16 bits of 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). A sinusoidal pulse with amplitude of 10V was selected as the input wave and to minimise the effect of background noise and improve the signal to noise ratio, twenty sampled signals were stacked. The shear wave propagating in a vertical direction ($V_{s(vh)}$) was monitored and the travel time was measured across the tip to tip distance between the transmitter and receiver elements (L_{tt} , Figure 2). In this study, it was found that testing frequencies (varying from 1.4 to 50 kHz) having a ratio between wave path length (L_{tt}) and wavelength (λ) exceeding 2 (e.g. Leong et al., 2005) were adequate to minimize the effect of the near-field component effect and warrant the strength of the received signal (Figure 3a). 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:

$$V_s = \frac{L_{tt}}{\Delta t} \quad (2)$$

$$G_0 = \frac{\gamma}{g} V_s^2 \quad (3)$$

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. The tests were conducted in a series of steps where the shear wave velocity was measured at an unconfined specimen first, and then different isotropic confinement pressures were applied (intervals of 50kPa pressure up to 250kPa). In each step, the axial displacement was monitored using a LVDT (accuracy of ± 0.025 mm). Typically 1 hour periods were sufficient to complete the isotropic compression and V_s was subsequently measured. These tests were carried out under constant water content conditions, in an attempt to replicate the expected field conditions and the compression criterion adopted was based on the variation of axial strain (i.e. $< 0.01\%$).

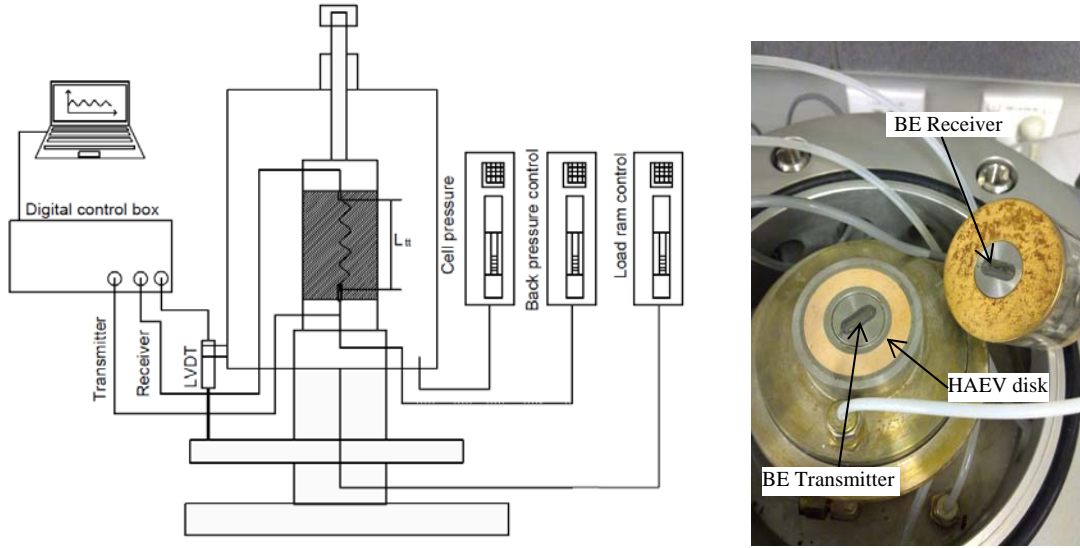


Figure 2. Bender element (BE) set-up in the triaxial chamber (left) and detail of the bender elements embedded in the top cap and bottom pedestal with an high air entry value (HAEV) ceramic disk (right).

3 EXPERIMENTAL RESULTS AND DISCUSSION

An example of the shear wave time domain series obtained for specimens compacted at water contents ranging from 8.5% to 16.5% are given in Figure 3b. In general, the shear wave velocity on the compacted specimens under unconfined condition remained approximately the same or in a similar order of values on the dry side (Figure 3b and 4a). Just before attaining the optimum moisture content (OMC), the shear wave velocity is observed to decrease sharply towards a minimum value at the higher moisture contents (Figure 4a). This tendency, obtained for all compaction energy levels can be attributed to the increase in dry unit weight inter-related to the decrease in suction together with the corresponding change in the soil structure (Delage et al., 1996). Noteworthy is the overlapping of V_s values obtained when OMC for each energy level is exceeded. In this range, V_s values are increasingly smaller for soil compacted under increasing larger compaction effort. This indicates that increasing the compaction energy in the field does not necessarily yield higher shear stiffness. These results are consistent with the well-known field overcompaction effect, which is caused by applying excessive energy to the lift. Figure 4b shows the data re-plotted in terms of degree of saturation. It can be observed that the data points belonging to different energy levels seem to reproduce a unique relationship. V_s value is nearly constant for $S_r < 0.67$ and it starts to decrease linearly with increasing degree of saturation for

$0.67 < S_r < 0.83$ and decreases abruptly when the degree of saturation value of 0.83 (line of optima, Figure 1) is exceeded. This is associated with the change in the soil structure from an aggregated structure in the compaction plane dry side to a matrix structure on the compaction plane wet side (Heitor et al., 2013).

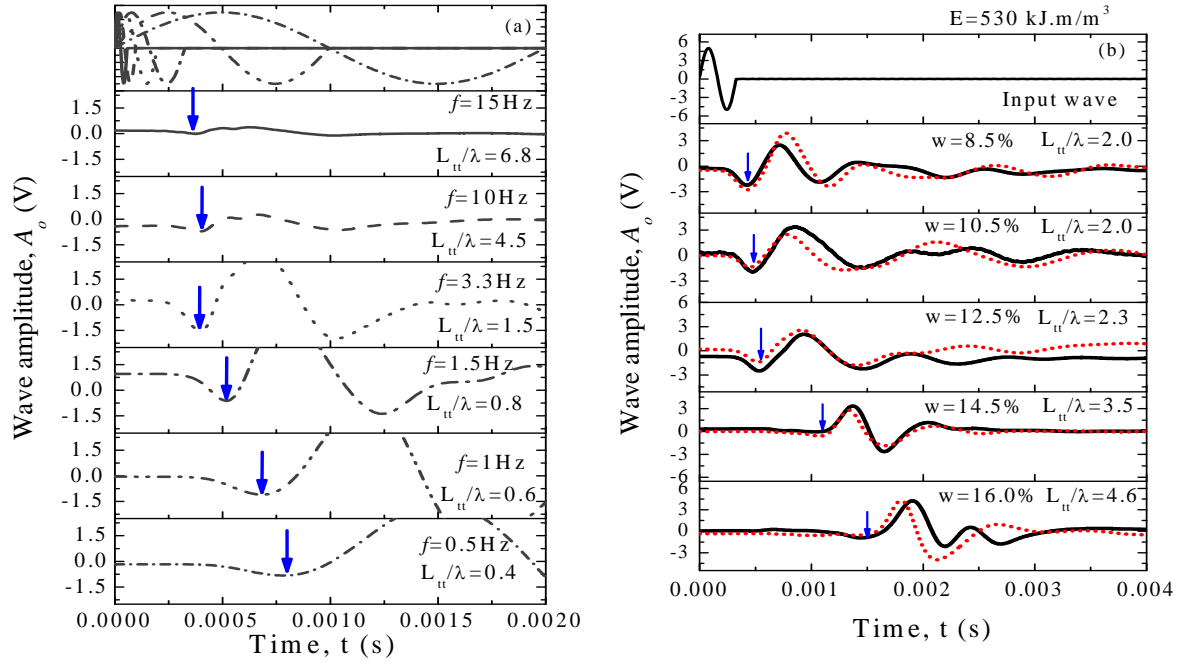


Figure 3. Typical V_s traces for (a) different testing frequencies (0.5 to 15 kHz) and (b) identically compacted specimens ($E = 530 \text{ kN.m/m}^3$, arrows indicate the travel time to the first maximum bump).

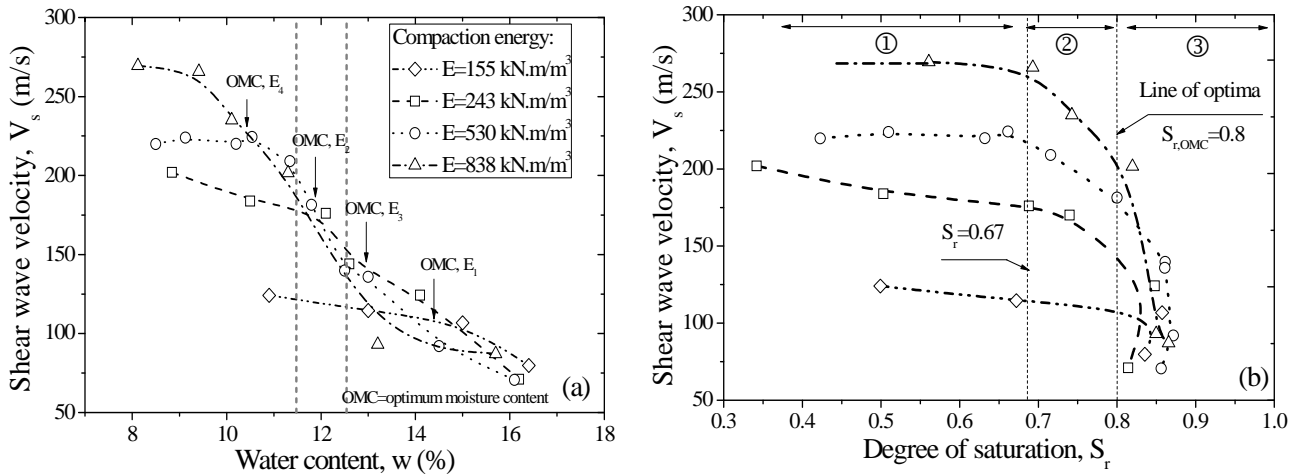


Figure 4. Variation of shear wave velocity with (a) moisture content and (b) degree of saturation obtained for different compaction energy levels adopted.

In the field, V_s values are obtained for different depths, to reproduce this effect in the laboratory, a series of compacted specimens were subjected to increasing confining pressures under content water content condition. Figure 5(a) illustrates a typical result of V_s with applied isotropic confining pressures (up to 250 kPa) for specimens compacted at 530 kN.m/m^3 . In general, the V_s shows an increase with increasing confining pressure for all energy levels, although the rate of increase is slightly different. A higher V_s increase was observed for specimens compacted at a higher water content, specifically those prepared at the wet side of OMC, i.e. $w = 14.5\%$ and $w = 16.5\%$ owing to their larger compressibility. The V_s - w

representation with increasing confining stresses shows that across the different water contents the tendency observed for ‘as-compacted’ condition still prevails. This result contrasts somewhat with the data obtained by Claria and Rinaldi (2007), who reported a substantial increase in V_s with increasing confinement on the specimens belonging to the wet side of OMC. This difference may be attributed to the fact that constant water conditions were not assumed.

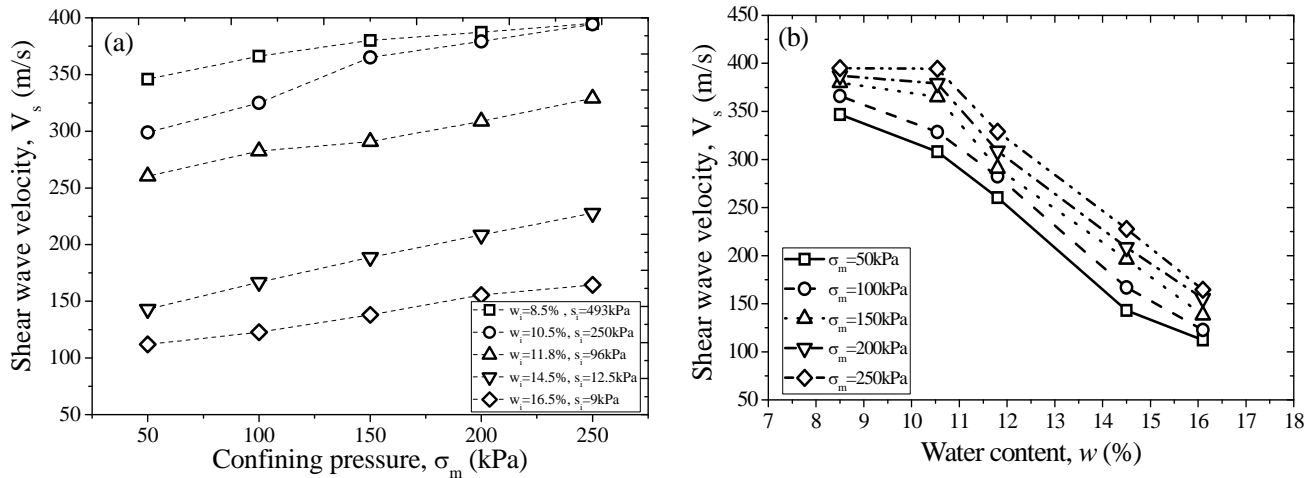


Figure 5. Variation of V_s (a) with increasing confining pressure and (b) with water content for specimens compacted with energy of $E_2=530 \text{ kN.m/m}^3$.

A total of 3 compacted specimens were tested using bender elements under isotropic confined conditions for V_s evaluation under wetting and drying cycles to investigate the impact of climatic changes in the V_s response. An isotropic confining pressure ($\sigma-u_a$) of 50 kPa (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. The adoption of this value was largely based on the Thornthwaite moisture index (TMI) distribution in Australian territories. The three specimens selected were prepared at water content of 12% with higher compaction energy levels. The variation of V_s between the drying and wetting branches is depicted in Figure 6. The most striking aspect, is that V_s exhibits higher values when following the wetting paths. This can be associated with the soil-water exchange in soil pores due to the hysteretic response observed in the soil water retention curve (i.e. the ink-bottle effect, which is related to the existence of large pores connected through smaller pores). In addition, the soil fabric is also evolving into a more constricted porosity centred at the microporosity range when the soil dries, and partly recovering some of the macroporosity when it is wetted (e.g. Monroy et al., 2010). These results are also consistent with the studies on decomposed tuff conducted by Ng et al. (2012). Nonetheless, the V_s hysteresis amplitude shows some differences among the three specimens, for instance at a suction of 25 kPa the energy level of 243 kN.m/m^3 is about 30 m/s, while for energy levels of 530 kN.m/m^3 and 838 kN.m/m^3 , and it is around 17 m/s and 16 m/s, respectively. This difference in the V_s hysteresis amplitude is likely associated with the initial compacted soil macrostructure (e.g. Heitor et al., 2013). Interestingly, the specimen prepared at the 243 kN.m/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 of nearly double compared to the specimen prepared at equivalent Standard Proctor. This seems to indicate that the dynamic behaviour of earth structures exposed to changes in hydraulic regimes varies and should be considered particularly for cases where the fills may have been inadequately compacted.

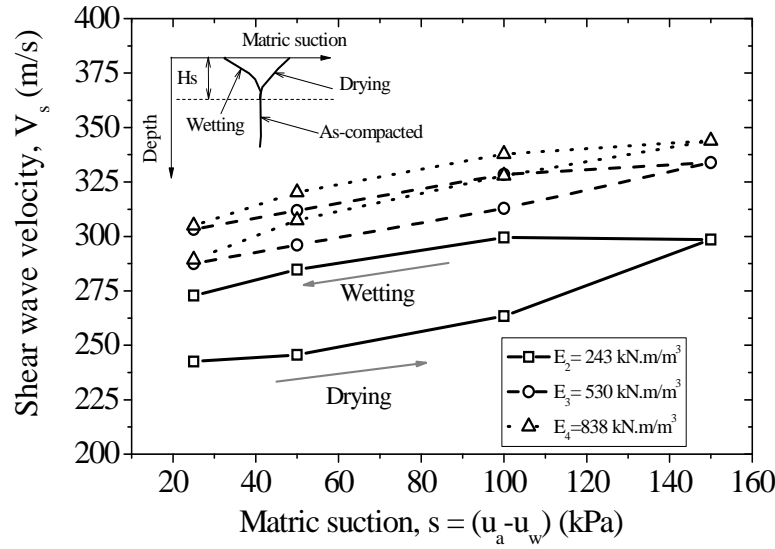


Figure 6 Variation of V_s with suction during a drying-wetting cycle of specimens prepared at energy levels of 243 kN.m/m^3 , 530 kN.m/m^3 and 838 kN.m/m^3 (modified after Heitor et al., 2014b)

4. CONCLUSION

From a number of Bender elements tests performed in compacted silty sand specimens, it was noted that the shear wave velocity varies with different compaction states (moisture content and compaction energy). A strong inter-dependent relationship between the degree of saturation and level of compaction energy could be found from the laboratory data. This study demonstrated that the shear wave velocity was influenced predominantly by the imparted compaction energy on the dry side compaction plane, where an increase in energy corresponds to an increase in V_s ; and on the wet side is likely influenced by the change in macrostructure, i.e. V_s decreased with the compaction effort. Furthermore, experimental data also confirms that in the assessment of the current conditions of compaction fills (i.e. dry unit weight estimation, shear strength), the use of shear wave velocity values alone are not sufficient, because V_s remains approximately constant across the compaction plane dry side. Thus, an additional variable is required. The experimental data showed that suction-moisture content in the compacted specimens is relatively independent of the compaction energy level. In fact, suction can be related to moisture content using a logarithmic linear expression. While the field evaluation of suction is not readily available, the measurement of moisture content is. Like this, to assess the current field conditions of given compacted fill, shear wave velocity surveys (e.g. SASW, HVSr) would have to be conducted in conjunction with the field evaluation of moisture content, using semi-destructive techniques (e.g. TDR probes, electrical resistivity tomography). Once the field values are known, they can be compared with the V_s - w relationship established for specimens compacted with standard compaction effort and a pass/fail criterion can be ascertained based on the importance of superstructure and shear strength requirements. The only limitation to the application of the methodology described is for the near-surface layers of old compacted fills which were likely exposed to rainfall and temperature variations over time. However, since these changes are likely restricted to a small near-surface fringe (H_s) that can be readily estimated using TMI, the described methodology could be used to assess current compaction conditions below that level.

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