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Effect of compaction energy on shear wave velocity of dynamically compacted silty sand soil

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Effect of compaction energy on shear wave velocity of dynamically compacted silty sand soil

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ABSTRACT: This study was focused on the effects of compaction energy on the dynamic properties of a silty sand in its as-compacted state in relation to the measured values of matric suction. The influence of the imparted energy on the shear wave velocity and the small-strain shear modulus of the compacted soil was studied for three different energy levels that correspond to the standard Proctor as well as reduced and enhanced. The specimens were prepared with moisture contents ranging from the dry to wet of optimum, and subsequently compacted to known dry unit weights for which the corresponding matric suction and shear wave velocity were measured. While a non-destructive technique adopting Bender elements was used to determine the shear wave velocity, the matric suction was evaluated using the filter paper method. Test results reveal that the shear wave velocity increases with the level of imparted compaction energy and the associated matric suction developed in the compacted soil. However, the change in shear wave velocity along the compaction curve is very significant. Pronounced compaction energy dependence is observed on the dry side of the optimum moisture content, whereas on the wet side of the optimum the matric suction governs the variation in the shear wave velocity

KEYWORDS: shear wave velocity, unsaturated soil, matric suction, compaction energy

1 INTRODUCTION

Compaction procedure to improve the geotechnical characteristics of soil has been widely applied in most construction works such as road and railway embankments, dams, landfills, airfields, foundations and hydraulic barriers.

The laboratory compaction characteristics of the soil govern the selection of adequate criteria to evaluate field compaction. These criteria are often characterized by setting a minimum deviation interval for the field dry density and moisture content compared with the laboratory obtained standard compaction curve, especially the two key parameters: maximum dry density and optimum moisture content. The desired engineering properties of compacted fills (e.g. compressive, shear and tensile strength, permeability and stiffness) can be established by imparting to the soil a given compaction energy. Conversely, the compaction energy applied in the field may not always be constant, because of the differences in the hydration time and lift thickness. These differences can induce substantial effects on the stress-strain behavior of the compacted soil (Seed and Chan, 1956). Usually the fills are placed at or near the optimum moisture content (OMC), hence, at the time of construction the compacted soil is in an unsaturated condition, whereby the matric suction resulting from the interaction of soil-water-air phases, characterize the mechanical and hydraulic behaviour of the compacted soil (Fredlund and Rahardjo, 1993).

The dynamic properties of the soil such as the shear wave velocity (Vs) or shear modulus (G) are important in the description of the engineering behavior under cyclic loading, for instance in relation to vibrations caused by traffic of heavy and fast moving vehicles, heavy earthworks machinery, earthquakes, among others. In these circumstances, the strain level is small and the shear modulus can be defined by a small-strain shear modulus (G_0), obtained using the shear wave velocity (Equation 1).

$$\boldsymbol{G_0 = \rho_b V_s^2} \qquad (1)$$

where ρ_b = total density and V_s = shear wave velocity of the soil mass.

When evaluating the shear stiffness in a compacted soil, it is expected that the matric suction has a significant role to play. Indeed, the influence of matric suction on the shear stiffness of compacted soil has been investigated in numerous past studies. There seems to be a common agreement among such previous studies that the increase of matric suction contributes to the increase of the stiffness of the soil skeleton, which in turn, yields higher shear stiffness values (Alonso, 1998; Cho and Santamarina, 2001; Claria and Rinaldi, 2004; Mendoza and Colmenares, 2006; Ng and Menzies, 2007, Sawangsuriya et al., 2008). Furthermore, the matric suction, soil structure, initial void ratio and the applied external confining pressure have been identified as the most relevant parameters that control the shear stiffness behavior of compacted soils (Santamarina el al., 2001). However, only a very limited studies have investigated the effect of compaction energy on the shear stiffness of compacted soil.

This paper examines the effect of compaction energy on the dynamic properties of compacted soil, namely the shear wave velocity and the small strain shear modulus. Specimens compacted at moisture contents ranging from dry to wet of OMC under three different levels of compaction energy have been considered in this paper. The main objective has been to establish the inter-dependent relationships among the shear wave velocity, small strain modulus and the matric suction of the as-compacted soil specimens.

2 EXPERIMENTAL WORK

2.1 *Soil type*

The soil used in this study was a silty sand soil, classified as SP-SM (Unified Soil Classification System, USCS). The soil is a byproduct of cobble quarrying activity by the Penrith Lakes Development Corporation and it has been used widely as an embankment fill in Penrith, Australia. Its main properties are listed in Table 1 and the particle size distribution curve is given in Figure 1.

Table 1. Main properties of silty sand soil

Properties	Sandy silt soil
Liquid limit (%)	25.5
Plasticity index	10
Cu (Coefficient of Uniformity)	5.0
Cc (Coefficient of Curvature)	0.99
Specific gravity	2.7

The soil consists of particle sizes ranging from cobbles to silt size. For testing feasibility, the larger size particles were removed and the material was air dried and then carefully desegregated using a mortar and pestle so that the particles could meet the nominal size of 2mm.

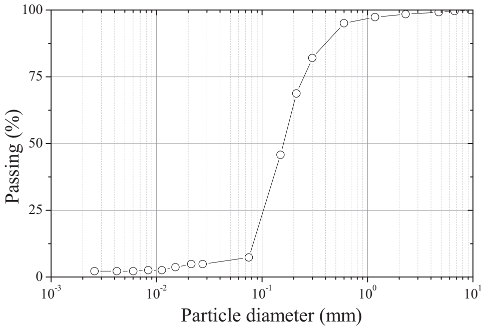

Figure 1. Particle size distribution of the silty sand soil.

2.2 *Testing program*

The testing program comprised the execution of compaction tests over a wide range of moisture contents. The required amount of water was added to the sample and then thoroughly mixed with a masonry trowel. The mixture was transferred to a plastic bag, and left overnight at constant temperature and humidity to ensure a uniform distribution of moisture. The Proctor compaction test (AS1289.5.1.1-2003) was conducted under three different levels of compaction effort, corresponding to 15, 25 and 35 blows per layer representing the reduced, standard and enhanced energy levels, respectively. For the shear wave velocity measurements additional specimens were compacted in a 50mm diameter mould following the procedure described by Sridharan and Sivapullaiah (2005). Figure 2 represents the compaction curves obtained from samples compacted under these three energy levels.

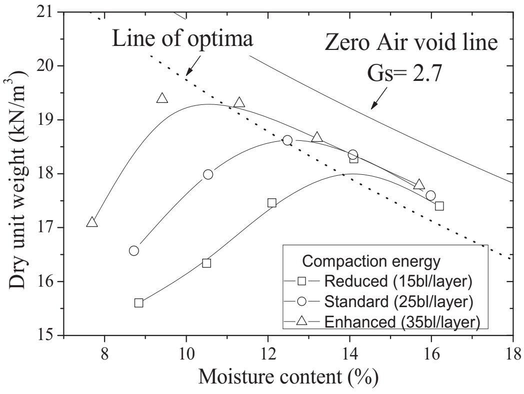

Figure 2. Compaction curves obtained for reduced, standard and enhanced compaction energies.

Shear wave velocity in the compacted specimens was measured using a non-destructive technique adopting bender elements. To determine the matric suction, the filter paper method was used due to its simple execution and the wide range of suction that can be measured using this technique.

2.3 *Shear wave velocity and suction*

The shear wave velocity propagation in the compacted specimens was determined using Bender elements. A pair of Bender elements adapted in the standard triaxial cell set-up apparatus was able to generate and detect shear waves throughout the unsaturated (compacted) soil specimens. The signal generation was controlled by software designed by GDS Instruments (UK) and a sinusoidal pulse was transmitted through the specimen. The data acquisition system had 2 input channels, with 16 bits resolution each and a sampling rate of 300 kHz. In order to minimize the influence of background noise, a series of twenty sampled signals were staked. In this way the signal-to-noise ratio could be maximized. The shear wave velocity propagating in the vertical direction, with the soil particles vibrating in horizontal plane (horizontal polarization) was monitored and the travel time was measured across the whole vertical length of the specimen (approximately 100mm). A testing frequency of 3.03kHz was adopted so that the testing variables could approximate the intervals previously proposed in the literature (i.e. Leong et al, 2005 and Arulnathan et al, 1998) without compromising the strength of the received signal.

The shear wave velocity was computed considering the effective length (L_{tt}) that corresponds to the tip to tip distance between the transmitter and the receiver, and the travel time (t). The tip to tip distance was determined using a digital caliper. The travel time was taken as the average of the travel times obtained by characteristic peaks and cross-correlation between the first arrival and first reflection traces (Vigianni &Atkinson, 1995 and Alramahi et al, 2007). The first deflection method yielded slightly lower values than the two previous ones. This difference can be attributed to the earlier arrival of the compressive waves or the near fields effects (Santamarina et al, 2001).

The filter paper technique was used to evaluate suction in the compacted specimens and it was conducted in accordance with ASTM D5298, 2003. The filter paper used is this study was 55mm Whatman No.42 (ashless). Both matric and total suction can be measured using contact or the non-contact methods, respectively. In the majority of the tested specimens, the contact method was utilized. However for the specimens compacted on the dry side of OMC, trimming the specimens for viable test samples was proven to be difficult at times, due to its brittle nature. For those specimens, non-contact method was used and the total suction was measured instead. The influence of osmotic suction was considered negligible since the content of salts in the tested soil was very small or non-existent. The equilibration time adopted was typically 7 to 10 days. Matric or total suction was computed based on the filter paper moisture content using the bilinear calibration curves given in ASTM D5298. For each compacted specimen a minimum of two filter paper determinations were performed, and the suction value was taken as the average between the results of at least two tests.

3 RESULTS AND DISCUSSION

An example of the results for the shear wave time domain series for a specimen compacted at OMC under standard compaction effort is represented in Figure 3. The most common methods for interpreting BE results regarding the estimation of the wave travel time are also illustrated.

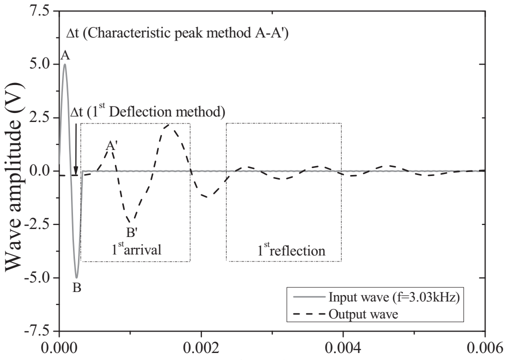

Figure 3. Shear wave trace for a specimen compacted at optimum moisture content under standard compaction energy.

The shear wave velocity in compacted specimens ranged from 350m/s on the dry side of OMC with the highest compaction energy to 80m/s on the wet side with lowest compaction energy. In general, the values of shear wave velocity on the compacted specimens remained approximately the same or in a similar order of values on the dry side. Just before attaining the optimum moisture content, the shear wave velocity is observed to decrease sharply towards a minimum value at the higher moisture contents (Figure 4).

This tendency, obtained for all compaction energies can be attributed to the increase in dry density inter-related to the decrease in suction together with the corresponding change in the soil structure. Figure 4 also shows that in the dry side of OMC, the shear wave velocity values seem to be controlled by the compaction energy imparted to the soil, since an increase in energy translates into an increase in the shear wave velocity. However, on the wet side of OMC, the suction tends to govern the changes in the shear wave velocity that seems to converge at the higher moisture contents. Noteworthy are the lower V_s values obtained on the wet side of OMC under the highest compaction energy, indicating that increasing the compaction energy in the field does not necessarily yield higher shear stiffness. Similar findings were obtained by Turnbull and Foster, 1956 while studying the mechanical strength using CBR tests for field compacted lean clays.

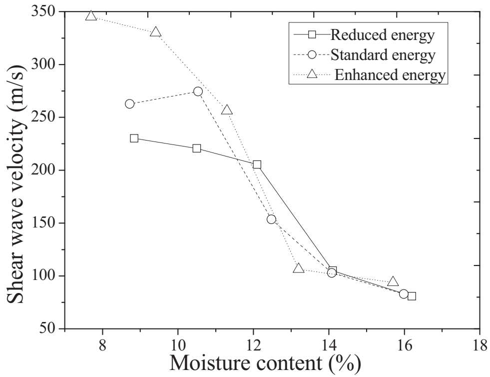

Figure 4. Shear wave velocity with moisture content obtained for reduced, standard and enhanced compaction energies.

Figure 5 represents the results of shear wave velocity, suction and dry unit weight for the standard compaction energy. It can be observed that shear wave velocity remains around a similar order of values on the dry side of optimum and decreases sharply on the wet side. With the progressive increase of the dry unit weight, the soil skeleton stiffens and the wave velocity is expected to increase. Concurrently, the decrease in suction contributes to the weakening of contact stresses acting on the soil skeleton, hence the wave velocity is expected to decrease. The balance of these parameters on the dry side of OMC causes the wave velocity to remain approximately constant. Furthermore, when the compacted soil moves closer to OMC the soil structure changes considerably. Microstructural studies conducted by Delage et al. (1996) on compacted silt revealed that the structure varies mainly from a wide pore distribution (dry side) to a more constrained pore distribution (wet side). This change seems to be responsible for the sharp decrease in the wave velocity just before attaining the OMC.

With the increasing moisture content, matric suction decreases even further. After exceeding OMC, the dry density commences to decrease. This also results in an abrupt decrease in the shear wave velocity. These results highlight the importance of suction effects on shear wave velocity in compacted specimens, as also described by Claria and Rinaldi, (2007).

The suction values obtained for the compacted specimens are depicted in Figure 6. They vary from 580kPa on the dry side to 5kPa on the wet side of OMC. In these tests, the amount of suction developed by compaction process was not very high owing to the fact that the clay fraction in the tested soil is nearly absent. Overall, the suction decreases with the increasing moisture content.

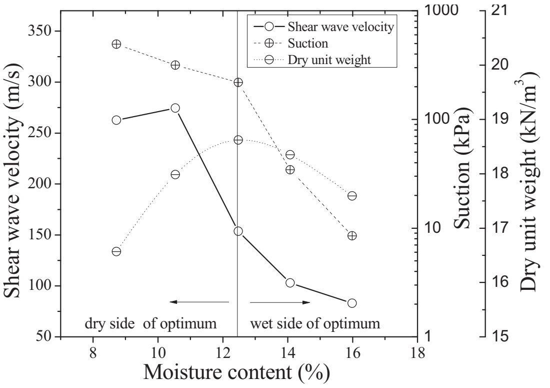

Figure 5. Shear wave velocity, suction and dry unit weight representation for specimens compacted under standard compaction energy.

Moreover, the specimens compacted at standard compaction energy exhibit the highest suction values particularly around the optimum moisture content. This suggests that the moisture content influence on suction is considerably more important than the compaction energy. Olson and Langfelder (1965) and Sawangsuriya et al. (2008) have reported similar results for compacted specimens using static and dynamic compaction efforts, respectively.

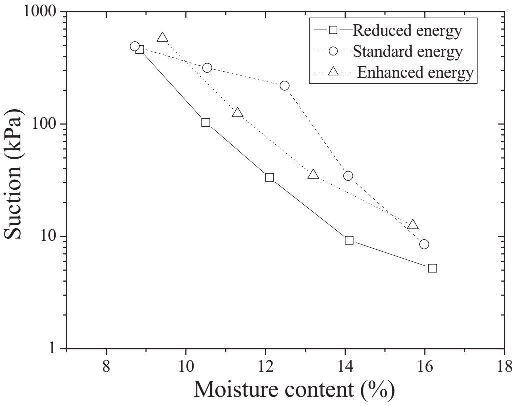

Figure 6. Suction with moisture content obtained for reduced, standard and enhanced compaction energy levels.

These curves resemble the soil-water characteristic curves (SWCC), which typically govern the hydraulic behavior of unsaturated soil. However, because the specimens compacted at different moisture contents yield different initial void ratios and soil structure; the points represented on Figure 6 merely illustrate the suction values obtained for as-compacted condition. In fact, each point could yield completely different SWCC curve as reported by Marinho and Stuermer, 2000 in their study on the influence of compaction energy on the SWCC curves.

3.1 *Compaction energy modeling*

Sawangsuriya et al. (2008), while studying the relationship between small strain shear modulus, suction, and moisture content in compacted specimens, proposed that the shear modulus could be determined as a function of the initial moisture content and suction (Equation 2).

$$\frac{G_0}{w} = \alpha \log(s) - \beta \tag{2}$$

where w = moisture content (%), s = suction (kPa) ; α = fitting parameter; and β = fitting parameter. Similarly, considering equation 1, the shear wave velocity can be expressed according with equation 3.

$$V_s = \left[\frac{w}{w/100 + 1}\,\frac{\alpha \log(s) - \beta}{\rho_d}\right]^{1/2} \tag{3}$$

where ρ_d = dry density(kg/m^3) given by (γ_d/g).

Considering the compaction energy, Equation 3 can be re-written as Equation 4 as proposed by Sawangsuriya et al. (2008).

$$V_s = \left[\frac{w}{w/100+1}\,\frac{E}{E_{std}}\,\frac{w_{omc}}{w_{omc,std}}\,\frac{\alpha \log(s)-\beta}{\rho_d}\right]^{1/2} \tag{4}$$

where E = compaction energy; E_{std} = reference standard compaction energy, E/ E_{std}= compaction energy ratio, w_{omc}= optimum moisture content at a given energy and $w_{omc,std}$= optimum moisture content under standard compaction effort.

In Figure 7, the experimental results are best fitted using linear regression analysis based on Equation 2. It can be observed that the Equation 2 generally describes the experimental trends; however, the correlation factors are slightly smaller than those obtained by Sawangsuriya et al. (2008) in clayey sand soils. This difference can be attributed to the difference in the soil properties of the material tested herein.

The empirical fitting parameters α and β obtained for each different energy level are listed in Figure 7. These parameters seem have a strong dependence on the compaction energy. Both increase with increasing compaction effort (Figure 8).

In Figure 9, the shear wave velocity determined using Equation 4 is plotted in contrast to the measured results of the compacted specimens.

The majority of the points are within 20% margin of error. One of the possible reasons for this discrepancy might be attributed to the different soil structures influence on the shear wave velocity, which prevails at different energy levels and is not accounted by Equation 4.

Furthermore, differences in the soil type might also constitute a source of numerous inaccuracies in the predicted results.

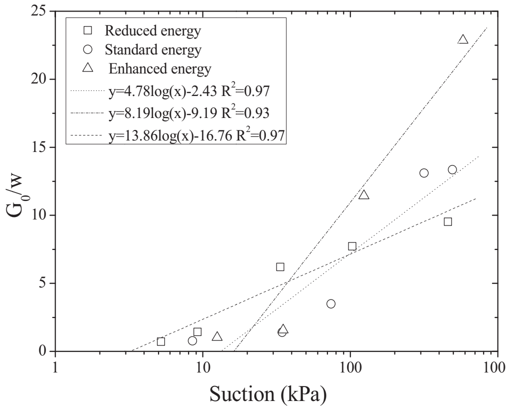

Figure 7. Normalized shear modulus with suction obtained for reduced, standard and enhanced compaction energies.

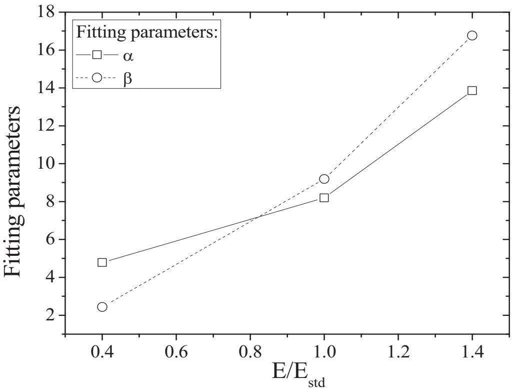

Figure 8. Fitting parameters obtained using Equation 2 with compaction energy ratio.

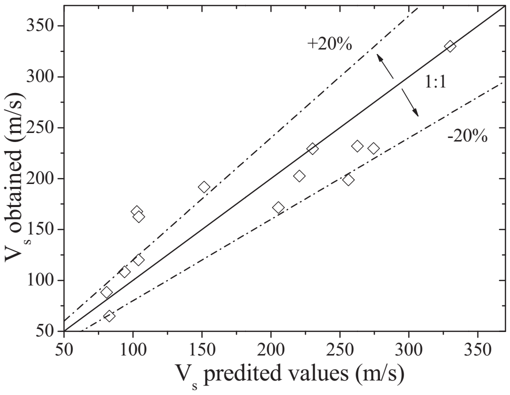

Figure 9. Comparison between the shear wave velocity values obtained and predicted using equation 4.

4 CONCLUSION

From a number tests performed in compacted silty sand specimens using Bender elements, it was observed that the shear wave velocity varies with the moisture content, soil structure and the imparted compaction energy. A strong inter-dependent relationship between matric suction and the level of compaction energy could be found from the laboratory data. This study has demonstrated that the shear wave velocity is predominantly influenced by the imparted compaction energy on the dry side of OMC, and by the matric suction on the wet side of the optimum.

The experimental findings also reveal that the shear wave velocity increases with the compaction energy on the dry side of the OMC, whereas it remains nearly constant or decreases gradually with the applied compaction effort over the wet side of OMC. This clearly suggests that in field compaction, the application of a higher compaction effort does not necessarily lead to superior shear stiffness. In fact, if the moisture content at the time of placement is slightly wet of the OMC, the increase of the number of compaction roller passes is likely to have a marginal effect on the resulting shear stiffness. The empirical equations proposed in a previous study (Sawangsuriya et al. 2008) were extended to accommodate the shear wave velocity data, and these new relationships could be successfully validated for the tested silty sand with a margin of error generally less than 20%. While this study offers an insightful outcome that relates the compaction energy to matric suction and shear wave velocity (hence soil stiffness) over a range of water contents on either side of the OMC, further studies will be required to examine whether a similar inter-dependence could be found for other soil types.

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