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CHARACTERISING COMPACTED SOIL USING SHEAR WAVE VELOCITY AND MATRIC SUCTION[1]

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ABSTRACT

The manner in which soil compacts governs the practical and reliable criteria in controlling compaction in the field. A nuclear density meter, based on radioactive isotopes, is the method most commonly used for field compaction, and while it performs well for controlling placement, its localised nature is not suitable for deeper fills or for assessing larger surface areas. In those types of conditions, alternative non-destructive methods should be considered. Numerous research studies have focused on the characteristics of compacted soil at its optimum moisture content under saturated conditions, but only a few have evaluated compacted soil under unsaturated conditions using surface wave and shear wave velocity surveys.

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 will compact, 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 construction works to improve the geotechnical characteristics of soil. The current conventional technique during construction using nuclear methods is based on an *in situ* determination of dry unit weight and moisture content. Estimating these variables using nuclear methods is advantageous because this instrument enables a rapid (i.e. seconds) determination in the field that in turn, smooths the progress of construction. However, these measurements are localised, which means there can be areas where insufficient compaction can occur. This poses problems with insufficient bearing capacity and differential settlements that involve high post-construction costs of maintenance. Moreover, in old compacted embankments, where few or no records of the control done at time of construction are available, there is no existing methodology that can help practicing engineers in their post-construction assessments. Thus, in these conditions, alternative techniques which can survey larger areas and greater depths (i.e.10-15 metres) should be considered.

Surveys of the shear wave velocity (i.e. MASW- Multi channel Analysis of Surface Waves) have been used extensively in engineering site investigations because they enable the characteristics of *in situ* material to be evaluated and used by practitioners to design foundations. Although this technique has generally been used to provide information on the shear strength of the underlying materials, using it to evaluate compaction characteristics has been limited. Since shear wave velocity propagates mainly through the soil skeleton, estimating the dry density based on wave propagation seems promising. Furthermore, the shear wave velocity can easily be related to the soil modulus, which is a variable commonly used in construction design.

Fills are usually placed at or near the optimum moisture content (OMC), so at the time of construction the compacted soil is unsaturated. This is why the matric suction resulting from the interaction of soil-water-air phases, characterises the mechanical and hydraulic behaviour of compacted soil (Fredlund and Rahardjo, 1993). Matric suction stress depends mainly on the pore size, void ratio, and fabric in a given soil, and can significantly contribute to increases in the mechanical properties (i.e. shear and compressive strength).

In general, shear wave propagation in a cohesive soil is mainly controlled by its mean effective stress, void ratio, and degree of saturation (Cho and Santamarina, 2001; Santamarina *et al.*, 2001). Past studies mostly concentrated on the characterisation of small strain shear modulus (G_0) or shear stiffness, for different degrees of saturation or matric

[1] This paper won the Sydney YGP Award in 2010.

suction. Indeed, it has been recognised that both matric suction and applied confining stresses play an important role in small strain shear modulus (Ng and Menzies, 2007).

This study explores the performance and cost effectiveness of using the shear wave velocity and matric suction to evaluate the field compaction characteristics, that is the void ratio or dry density. Laboratory studies conducted on compacted specimens over a wide range of moisture contents were used to evaluate the proposed empirical relationship. Furthermore, previous approaches mainly concentrated on investigating the propagation of shear wave velocity by considering a given soil structure and void ratio. By doing so, compacted soil was treated like a completely different soil. In this study the authors aimed to characterise compacted soil in a more holistic framework and, in order to accomplish this, the compaction history or soil structure was included in the proposed empirical equation.

2 TESTING PROGRAM

A testing program was undertaken over the entire compaction range of moisture contents. Bender elements were used to measure the shear wave velocity of compacted specimens, while a small tip tensiometer able to read up to 90-100 kPa (Soil Moisture Equipment Corporation), and the filter paper method for comparison and suction higher than 100 kPa, were used to determine the matric suction, and the pressure membrane extractor apparatus was used to determine the characteristic soil-water curve.

2.1 SPECIMEN PREPARATION

A silty sand soil, classified as SP-SM was used in this study. Its main properties are listed in Table 1. Prior to compaction the soil samples were air dried. The required moisture was then added to the sample and thoroughly mixed with a masonry trowel. The mixture was then transferred to a plastic bag and kept under constant temperature and humidity for overnight periods to ensure that the moisture was uniformly distributed. The samples were then remoulded in a 50 mm diameter compaction mould following the procedure described by Sridharan and Sivapullaiah (2005).

Additional specimens were compacted using the standard Proctor compaction mould (AS1289.5.1.1-2003), to serve as a comparison for the dry densities obtained in the 50mm diameter mould. The specific compaction energy used in the 50mm diameter mould was adjusted to meet the standard Proctor effort dry density values (Figure 1). The soil was compacted in 3 layers using 24 blows per layer, with an equivalent energy of 529kN.m/m^3. Six samples were prepared with a range of moisture contents, -4% of optimum, -2% of optimum, optimum, +2% of optimum, +4% of optimum.

Table 1: Properties of the tested soil

Properties	Silty Sand
USCS classification [a]	SP-SM
Liquid limit	25.5
Plastic index	10
Sand (%)	79%
Fines (%)	21%
Cu Coefficient of Uniformity)	5.0
C_c (Coefficient of Curvature)	0.99
Specific gravity	2.70

[a] – Unified soil classification soil symbol

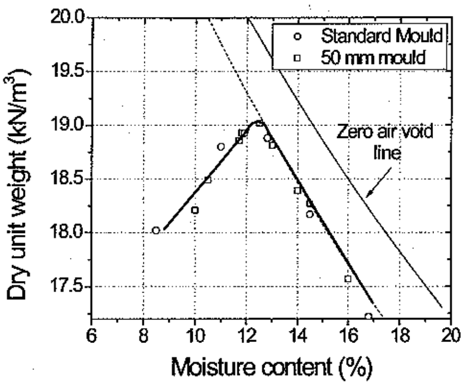
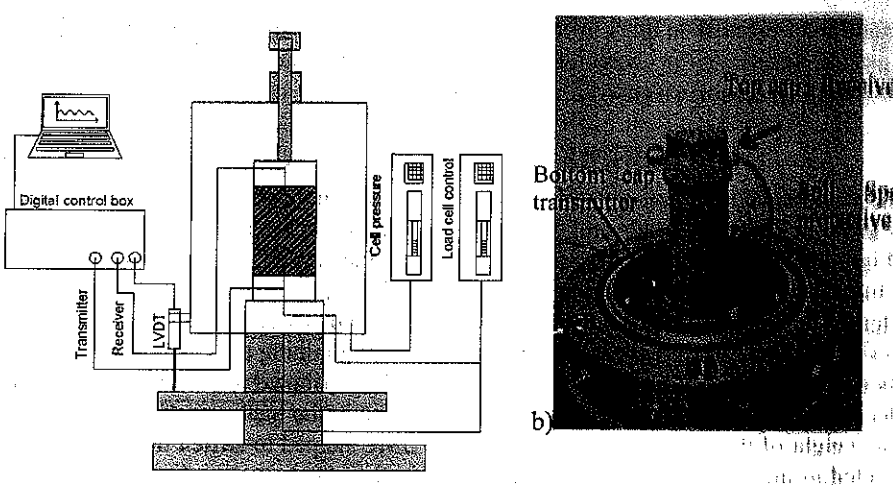


Figure 1: Compaction curve considered.

2.2 SHEAR WAVE VELOCITY IN COMPACTED SOIL

The shear wave velocity in the specimens was determined using bender elements. In order to investigate the effect of isotropic confining pressure on the shear wave propagation, a pair of bender elements was adapted in the standard tri-axial cell apparatus. The transmitter element, located on the bottom platen, bent as excitation voltage was applied, converting it into the mechanical energy responsible for generating an input wave. The receiver signal was then captured by the top platen receiver bender element, which converted mechanical energy into voltage that could be read on an oscilloscope (Figure 2a). The signal generation was controlled by software designed by GDS Instruments (UK). The data acquisition system had 2 input channels, with 16 bits of resolution each, and a sampling rate of 300 kHz. A sinusoidal pulse with amplitude of 10V was selected as the input wave so that the soil - bender elements interaction could be maximised. To minimise any background noise, twenty sampled signals were staked. In this way the signal-to-noise ratio could be maximised. The shear wave propagating in a vertical direction, while the soil particles vibrated in the horizontal plane ($V_{s(vh)}$) was monitored and the travel time was measured across the whole vertical height of the specimen (approximately 100 mm).



a) b)

Figure 2: Bender element set-up in the triaxial chamber with bender elements adapted in the top and bottom platens and illustrative photograph

A testing frequency of 3.33kHz was used to ensure optimum testing variables, as suggested by previous studies (i.e. Leong *et al.*, 2005 and Arulnathan *et al.*, 1998). The shear wave velocity (V_s) was computed as the ratio between the effective length L_{tt} (the tip-to-tip distance between the transmitter and receiver) and the travel time *t*. The tip- to-tip distance was easily determined using a digital calliper, but evaluating the wave travel time was more complex. In this study, three different methods were used, first deflection, characteristic peaks, and cross correlation.

Generally, the travel times based on the first deflection method were slightly smaller than the other two methods. This difference was probably related to the near field effects caused by interference from the earlier arrival of the compressional waves (Santamarina *et al.*, 2001). For this reason, travel time was taken as an average of the times obtained by the characteristic peaks and cross correlation methods.

The tests were conducted in a series of steps where the unconfined shear wave velocity was measured first, and then different isotropic confinement pressures were applied using a triaxial chamber (intervals of 50 kPa pressure up to 250 kPa). At each step, a one hour period was allowed to pass to ensure that the compression of each sample had occurred before measuring V_s. The specimens subjected to increasing confinement were more likely to show some volumetric change (i.e. compression), therefore it is important to monitor any variation of wave travel length (L_{tt}) during the tests. To achieve this, a LVDT (linear variable differential transformer) was attached to the exterior of the triaxial cell (Figure 2a). At each step the load cell pressure controller was adjusted to allow the load piston to touch the top cap of the specimen, without applying any load. Thus the axial compression or volumetric strain (since E_v=3E_a in isotropic conditions) could be measured.

2.3 MATRIC SUCTION DETERMINATION

The matric suction was measured using the filter paper method and a small tip tensiometer (Soil Moisture Equipment Corp.). Although both methods have been widely used in geotechnical applications, there are particular advantages associated to each one. The filter paper method is a relatively simple and inexpensive technique well able to measure suction over a wide range, but it does require a longer equilibration time (7-10 days). By way of contrast, the measurements taken with a small tip tensiometer are rapid (i.e. a matter of minutes), but are limited to the low range suction (up to 100 kPa). A 55 mm Whatman No.42 (ashless) filter paper was selected and the contact method was conducted according to ASTM Standard D5298 (2003). In this method, filter paper is placed in contact with the sample during equilibration time, typically 7days, then its moisture content is measured and the bi-linear calibration curve given in ASTM D5298 is used to determine the related matric suction values. Matric suction was also measured with a small-tip tensiometer from the Soil Moisture Equipment Corp., according to ASTM Standard D3404-91 (1998). A comparison of the results showed that both methods responded similarly in the low suction range (up to 70 kPa), but in the medium and high ranges (>70 kPa – 10 MPA), the small tip tensiometer performed poorly because its capability had been exceeded. The versatility of this instrument and its rapid matric suction measurements render it the most adequate for controlling suction in the field but due care should be taken because its measuring capability is rather limited.

Matric suction measurements were conducted in the compacted specimens before the triaxial confining pressure tests. During the isotropic confining pressure tests, matric suction was not measured and the tests were carried out under constant water content. It is reasonable to assume that the water content and suction remained approximately constant while the unsaturated specimens compressed because Kane (1973) found this to be true for specimens of loess with an initial degree of saturation lower than 80%. Additionally, representative specimens compacted at OMC, OMC-2%, and OMC+2% were used to determine the characteristics of the soil-water curve. A pressure membrane extractor apparatus using the axis translation technique was used for this purpose.

3 EXPERIMENTAL RESULTS AND DISCUSSION

An example of the shear wave time domain series obtained for specimens compacted at moisture contents ranging from 8.5% to16.5% is given in Figure 3. In general, earlier arrival times were detected for specimens compacted on the dry side of OMC. Figure 4a shows the experimental results of the shear wave velocity across the whole range of compaction moisture contents which varied between 70 m/s and 225 m/s on the wet and dry side of OMC, respectively. A characteristic tendency of the V_s and moisture content was found where Vs generally remains at a similar order of values on the dry side of OMC but it decreased sharply just before attaining the OMC and reached a minimum at higher moisture contents (i.e. wet side of OMC). This tendency may be attributed to a combination of an increase in the dry unit weight (or decrease in the void ratio) together with a decrease in the matric suction and change in the soil structure. An increase in the weight of the dry unit on the dry side of OMC helped to stiffen the soil skeleton, so the shear wave velocity was expected to increase. Concurrently, a decrease in the matric suction (i.e. by adding more water) helped to weaken the contact stresses acting on the soil skeleton, so the wave velocity was expected to decrease. The balance of these parameters on the dry side of OMC caused the shear wave velocity to remain approximately constant, although the structure of the soil changed considerably when the specimens were compacted at moisture contents closer to OMC. In fact, past studies using SEM (scanning electron microscopy) conducted by Delage *et al.* (1996) on specimens of compacted silt showed that the structure varied, mainly from a wide pore distribution (dry side of OMC) to a more constrained matrix dominated pore distribution (wet side of OMC). This change probably caused the sharp decrease in the wave velocity just before attaining OMC. After exceeding OMC, the dry unit weight decreased while the matric suction decreased even further, causing the shear wave velocity to abruptly decrease. These results highlight the importance of matric suction stresses on shear wave velocity in compacted specimens, as described by Claria and Rinaldi (2007).

Figure 4b illustrates the relationship between V_s and applied isotropic confining pressures (unconfined to 250 kPa). Overall the shear wave velocity increased with isotropic confining pressure, with a slightly higher rate of increase in the specimens compacted at the dry side of OMC, and at OMC. The change in volume recorded during triaxial confinement was computed in terms of volumetric strain, and is represented in Figure 5. Larger compressibility values were observed for the specimens compacted on the wet side. For moisture contents below the OMC, the shear wave velocity increased with the stiffness of the soil skeleton (reduced compressibility), whereas for higher moisture contents, as the capillary forces weaken the contact stresses (with the soil reaching higher degrees of saturation) compressibility was higher. What is worthy of note is that the lowest values of compressibility were seen in the specimens compacted at OMC (Figure 5). The soil water characteristic curves (SWCC) for three specimens compacted at 10.5% (dry side), 12.5% (OMC), and 14.01% (wet side) are shown in Figure 6. The experimental points obtained with the pressure membrane apparatus, were interpolated using the close-form expression suggested by van Genuchen (1980) (Equation 1).

$$S_{re} = \left[\frac{1}{1+(\alpha\psi)^n}\right]^m \text{ and } m = \left(1 - {}^1\!/_n\right) \qquad (1)$$

The parameters (α, m and n) used to fit the SWCC curves represented above, are summarized in Table 2. The air entry values (AEV) for the different curves were determined as shown in Figure 6.

Table 2: Summary of the SWCC parameters

van Genucten parameters	Dry of optimum curve	Optimum curve	Wet of optimum curve
α	0.32	0.13	0.22
m	0.15	0.14	0.1
n	1.17	1.16	1.11

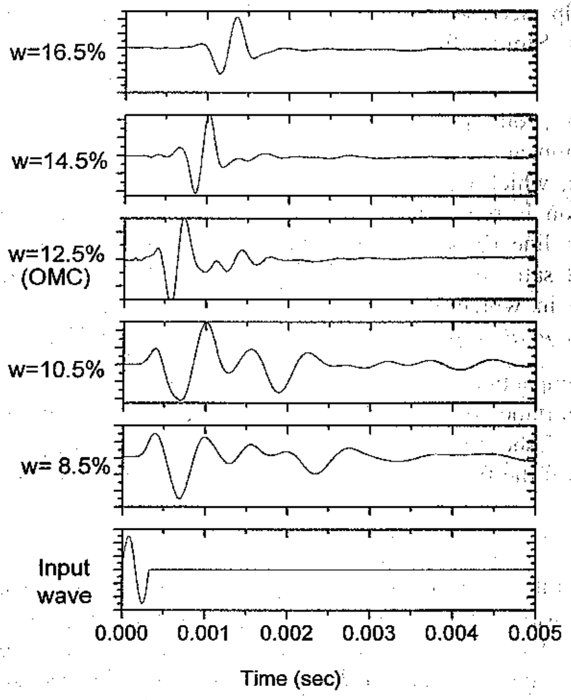


Figure 3: Shear wave velocity traces for different moisture contents.

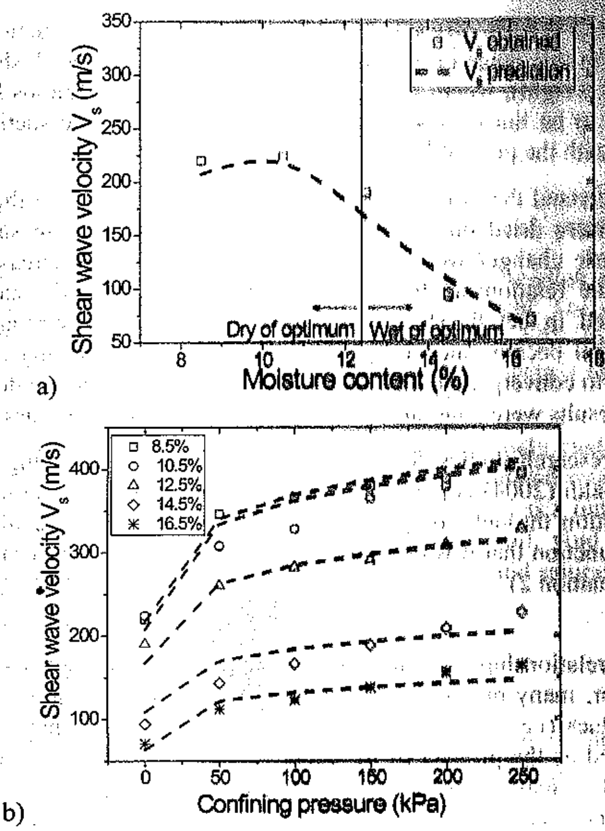


Figure 4: Shear wave velocity with moisture content (a) and confining pressure (b).

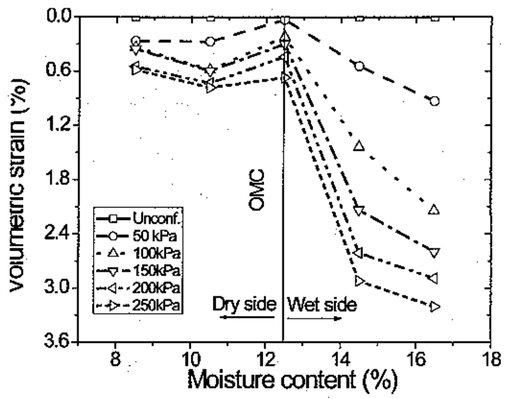


Figure 5: Volumetric strain with moisture content.

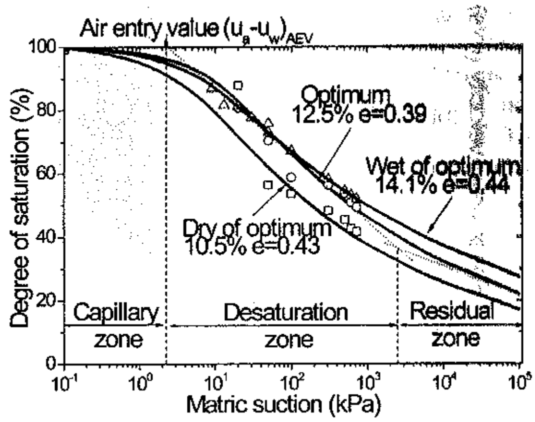


Figure 6: SWCC curves for specimens compacted at the selected moisture content using the interpolations by van Genucthen (1980).

4 PROPOSED EMPIRICAL RELATIONSHIP

The results of this study generally show that the propagation of the shear wave velocity in compacted soil is governed by a combination of the soil skeleton (particle arrangement or void ratio), applied confining pressure, and suction stresses. However, when the soil is compacted both the particle arrangement and change in the matric suction are derived from the difference in compaction history (i.e. compacted on the dry or wet side). To better understand the individual effect of these parameters, additional compacted specimens were prepared under different compaction energies (i.e. an increase in dry unit weight or decrease in the void ratio) and subjected to a drying process (i.e. an increase in the matric suction). Different void ratios were targeted by increasing imparted energy onto specimens compacted at 8.5% (dry side of OMC), because the matric suction values were reported to be independent of the energy applied in this range (Tarantino and De Col, 2009). Figure 7 shows the relationship between V_s and the void ratio (or dry unit weight), where it can be seen that smaller void ratios help increase the shear wave velocity, an increase that appears to be linear under approximately constant matric suction. Similar findings reported by Richart *et al.* (1970) agreed with the present results.

To understand the effect of the changes in matric suction in the V_s, four specimens compacted at 16.5% (wet side of OMC) were dried out to induce an increase in the matric suction at an approximately constant void ratio. Small volumetric changes were noticed as the matric suction increased, which derived from the drying process. Figure 8, where the relationship between V_s with increasing matric suction is represented, shows that these parameters are associated, in fact, the shear wave velocity increases almost roughly linearly with the logarithm increase of suction. And as the soil became increasingly desaturated (or lower degrees of saturation), the shear wave steadily increased and seemed to converge to a maximum value in the higher suction domain, which typically corresponds to the residual zone. These results were consistent with the findings reported by Vassallo *et al.* (2007) and Cho and Santamarina (2001).

In past research studies, few authors concentrated on describing compaction within one framework. The work by Claria and Rinaldi (2004) is noteworthy, in that they recognised the importance of matric suction in the shear wave velocity propagation through compacted silt. In their study, the unconfined shear wave velocity (V_{s0}) was described using a linear function that was dependent on the matric suction (u_a-u_w), and the fitting parameter k associated with the type of soil (Equation 2)

$$V_{s0} = k(u_a - u_w) \quad (1)$$

In this relationship the value of V_{s0} was taken as zero at a saturated state (where the matric suction equals zero). However, many previous experimental results showed that shear wave velocity in saturated conditions exhibits non-zero values (i.e. Mancuso *et al.,* 2002). It seems likely that the effect of matric suction on the values of V_s can be expressed as the product of its saturated value $V_{s,sat}$ and the matric suction function (Equation 3 proposed by Alonso (1998) for small strain shear modulus $G_{0,unsat}$). In this way V_s has its minimum value at saturated conditions (i.e. u_a-u_w=0) and increases when the soil enters the unsaturated domain. The rate of increase caused by an increase in the matric suction can be captured using an appropriate function of the matric suction $f(u_a$-$u_w)$.

$$V = V_{s,sat} f(u_a - u_w) \quad (2)$$

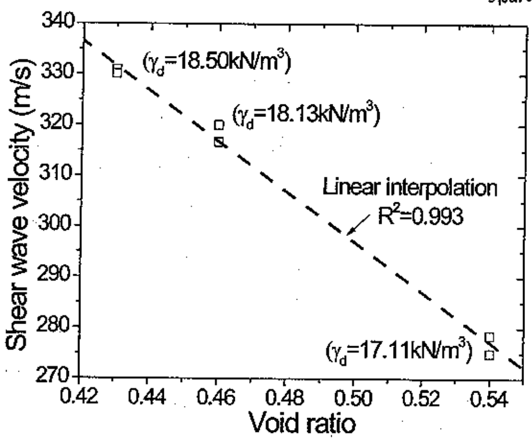


Figure 7: Shear wave velocity with increasing void ratio at approximately constant suction.

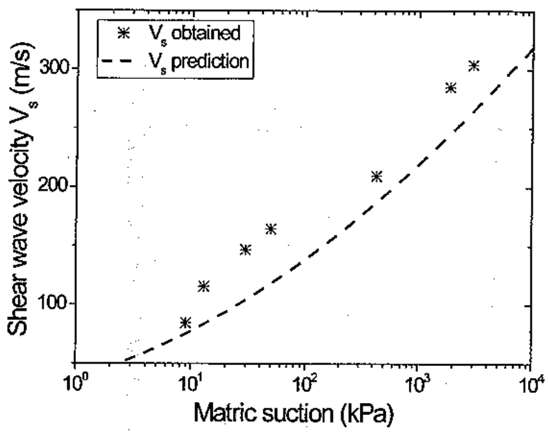


Figure 8: Shear wave velocity with matric suction (Drying process) at approximately constant void ratio.

However, in compacted soil, the void ratio and structure changed as the moisture content increased. To take this change into consideration, a parameter that relates the present state of the soil, namely relative density, should be introduced into the relationship.

A general mathematical model that relates the shear wave velocity (V_s) (propagation of the SV-wave), matric suction, compaction history, and saturated shear wave velocity ($V_{s,sat}$) for different soils and isotropic conditions, is expressed in Eqation 4 as,

$$V_s = V_{s,sat}\left[1 + D_r^* f(u_a - u_w)\right] \quad (3)$$

where D_r* is the relative density that accounts for the compaction history of the soil in relation to the maximum (AS 1289.5.1-1998) and minimum void ratio (lowest void ratio obtained by modified compaction effort), and $f(u_a$-$u_w)$ is the matric suction function that relates the post-compacted suction to the air entry suction as follows,

$$D_r^* = \frac{e_{\max} - e}{e_{\max} - e_{\min}^*} \tag{4}$$

and

$$f(u_a - u_w) = \log\left(\frac{\alpha(u_a - u_w)}{(u_a - u_w)_{AEV}}\right)^{\beta} \tag{5}$$

where the coefficients α and β are best fit parameters related to a given soil type. The matric suction function accounts for post-compacted state suction in relation to the air entry suction or AEV at optimum moisture content. The air entry value (AEV) is the value of the matric suction where air begins to enter the soil-water system. The AEV value was introduced into the expression so that the increase in V_s (controlled by bulk water) in the low matric suction range can be included (Mancuso *et al,,* 2002).

Determining the experimental saturated shear wave velocity under unconfined conditions was extremely challenging. There have been a limited number of proposed empirical relationships that accurately describe the saturated small strain shear modulus (Richart *et al.*, 1970, Stokoe *et al.*, 1995). The shear wave velocity can easily be derived as a function of the material parameter *a,* which is associated with the fabric or microstructure, and the type of soil, void ratio e, atmospheric pressure p_a (i.e. p_a=100 kPa), additional mean effective stress or confining pressure σ'_m and saturated bulk density ρ_{sat}; as given below (Equation 7),

$$V_{s,sat} = \sqrt{\frac{af(e)(\sigma'_m)^n (p_a)^{(1-n)}}{\rho_{sat}}} \tag{6}$$

where $f(e)=1/e^{1.21}$ is a function of the void ratio adopted, as proposed by D'Elia and Lanzo (1996) for sandy silts, and n is a stress exponent which is commonly less than unity (Richart *et al.*, 1970). The effect of confining pressure was introduced into the saturated shear wave velocity term. In this way, the shear wave velocity of compacted unsaturated soil is a function of the saturated shear wave velocity, matric suction, and compaction history.

The model predictions (dashed lines) are represented together with the experimental results (Figure 4a, Figure 4b, Figure 7 and Figure 8). The proposed relationship predicted the trend of the shear wave velocity along the compaction moisture content under unconfined conditions (Figure 4a) and for a range of applied confining pressures (Figure 4b). The shear wave velocity increasing with the void ratio is well captured (Figure 7), while the increase due to matric suction captured the experimental trends but slightly underestimated the wave velocity in the high suction range (Figure 8). The differences observed can be attributed to some degree of shrinkage that occurred while the specimens were drying (i.e. change of void ratio), which induced larger discrepancies in the model prediction, particularly in the residual matric suction range. The material and fitting parameters used in this study are listed in Table 2. These parameters are unique and adequately model the shear wave velocity over the complete range of compaction moisture contents, as well as under applied confining pressure.

Table 3: Summary of the Model parameters

Material Parameters		Fitting parameters	
a	75	n	0.23
e_{max}	1.04	α	1.04
e_{min}	0.27	β	23

5 CONCLUSION

From a number of bender element tests performed on compacted specimens of silty sand, the shear wave velocity varied with the moisture content and structure of the soil. Moreover there was a strong dependence on both matric suction and compaction history. The matric suction on dry side compacted specimens had a key impact on the shear wave velocity while the confining pressure greatly influenced the wave behaviour. The findings of this study show that the shear wave velocity increases with confining pressure but its rate of increase is different for the various initial soil structures. The compressibility of the specimens was monitored with increasing confining pressure. Substantially lower values were obtained for specimens compacted at optimum moisture content because the particles of soil were closer together.

A novel relationship considering the influence of matric suction, compaction history and confining pressure parameters on shear wave velocity was developed. The proposed empirical expression accurately described the unconfined wave velocity and reproduced, with a good degree of confidence, the strengthening of the soil skeleton due to isotropic confinement. Small inaccuracies that derived from drying the soil were found while modelling the wave velocity in the high matric suction range. It is expected that such inaccuracies would have almost no effect on these predictions. Generally, in a full size compacted embankment, only the top layer would be exposed to rainfall and temperature variations, so any significant changes in the moisture or matric suction would be restricted to the compacted surface layers only. Nevertheless, further testing is required to evaluate the influence of these seasonal climatic variations in shear wave velocity. A successful implementation of this method requires the determination of the field matric suction and shear wave velocity. Furthermore, the fitting parameters used for each type of soil must be benchmarked, but once the parameters are known, the void ratio for higher depths and large surface areas can be computed. Therefore, the degree of efficiency of the compaction process in a post-construction period can be determined, and active measures can be taken to minimise differential settlements and prevent embankment failure.

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