Soil Elastic Modulus Determined by Ultrasound Tests

W.S. Sarro, G.C.S. Ferreira

Abstract. The elastic constants obtained through conventional destructive (triaxial and resilience) tests can present great variability, even for soils with the same classification. Thus, a test is necessary to determine the elastic constants of soils in a reliable and replicable way. The ultrasonic technique is used to characterize rock and several construction materials (wood, cementitious matrices, metals), including the elastic parameters (elastic modulus, shear modulus, and Poisson’s ratio). The aim of this study was to verify the correlation between the elastic modulus obtained through ultrasonic testing and through a simple unconfined compression test on compacted clayey soil. Test specimens were molded at normal compression energy with three moisture contents; the specimens were exposed to air and packed with plastic wrap for 120 days. After this period, we performed ultrasonic and compression tests. The technique presented great potential to study the mechanical behavior, with correlation coefficients over 0.97 for both parameters (compressive strength and static elastic modulus). We also verified that the ultrasonic testing is influenced mainly by the moisture content.

Keywords: geotechnical, mechanical characterization, nondestructive testing, soil elastic behavior, soil moisture content, ultrasound transmission method.

1. Introduction

Defining the elastic constants of compacted soil is crucial for its correct application in geotechnical works (pavements, landfills, dams). However, the elastic modulus and the Poisson’s ratio are usually determined through empirical tests performed with laboratory specimens, which do not represent actual conditions of the material (Yang et al., 2015). These conditions become even more complex since the behavior of the soil regarding its deflection is not perfectly linear, with residual deflections occurring even in the strain x specific deflection curve (Dias, 2007). Thus, performing specific soil tests to determine the elastic modulus and Poisson’s ratio (triaxial compression, resilience) are not feasible due to the number of repetitions required for a correct and reliable characterization. Moreover, elastic constants obtained by these methods can present great variability, even for soils with the same classification.

Recent research indicates that nondestructive in situ testing techniques called cross-hole, down-hole and up-hole allow to determine the propagation velocity and consequently the elastic constants of soils in depth under low strain (Choo et al., 2018; Nejad et al., 2017; Pegah et al., 2017). Measurements are made inside the borehole and the technique is chosen depending on the position of the seismic sources in the holes. Although these tests can cover large volumes of soil, the preparation of the holes and the equipment have a high cost.

Champiré et al. (2016) and Miccoli et al. (2014) studied sandy samples through unconfined compression tests with determination of deflections; both studies achieved similar values of elastic modulus, between 2.20 and 2.80 GPa. In contrast, Bui et al. (2014a) and Lombillo et al. (2014) studied soils with the same classification and also used the unconfined compression test; their values were in the range 0.18 to 0.95 GPa. The contradiction in the literature reinforces the need for a test capable to determine the elastic constants of soils in a reliable and replicable way.

The ultrasonic testing is recommended to determine the elastic constants of compacted soils more easily. It is a nondestructive technique already applied in the characterization of several building materials (wood, cementitious matrices, metals). The velocity of longitudinal and transverse ultrasonic waves is required when ultrasonic testing is used to determine elastic constants. The application of elasticity theory to the longitudinal and transverse velocities determines the elements of the stiffness matrix, which, after their inversion, result in the flexibility matrix and consequently, in the values of the elastic modulus, of shear and of the Poisson’s ratio (Bucur, 2006; Bucur & Archer, 1984; Gonçalves et al., 2011a, 2014; Kohlhauser & Hellmich 2012; Vázquez et al., 2015). Materials may present isotropic, anisotropic or orthotropic behavior, thus, it is necessary to know their elastic properties to determine the matrix (Bui & Morel, 2009; Bui et al., 2014b; Christ & Park, 2009; Ferreira et al., 2014; Maillard & Aubert, 2014; Miccoli et al., 2015; Pietruszczak & Krucinski, 1989).

Some authors studied the application of the ultrasonic technique in compacted soil specimens and in constructive elements in soil. These studies involve the determination of preliminary data (ultrasonic velocity at the soil), the isotropy of the compacted soil (Christ & Park, 2009), the elastic constants (Cai et al., 2015; Hammam & Eliwa, 2013;...
Wang et al., 2006; Yu et al., 2016) and the definition of factors that can interfere in the ultrasonic pulse (Dongqing et al., 2016; Ferreira et al., 2014; Sarro et al., 2017; Teixeira et al., 2015).

The factors that may interfere in the ultrasonic pulse on soil and must be considered are both those already determined for other materials and those considered during the determination of the elastic constants of the soil by destructive methods. Vanapalli & Adem, 2014 (Adem & Vanapalli, 2015 and Oh & Vanapalli, 2016) describe void ratio, compaction energy and soil structure as interfering factors to determine the elastic modulus, therefore, they should also be considered for ultrasonic tests. The porosity, a parameter related to the void ratio, directly interferes in velocity (Chen et al., 2016; Luong et al., 2014) and must be considered in ultrasonic testing, because of the absorption and scattering of the ultrasonic pulse (Bauer, 2000; Cultrone et al., 2001; Lombillo et al., 2014; Qasrawi, 2000; Sarro et al., 2015).

Other studies indicate water content, soil density and type of transducer as factors that also interfere in ultrasonic velocity (Cardoso et al., 2017; Champiré et al., 2016; Chen et al., 2017; Dongqing et al., 2016; Ferreira et al., 2014; Sarro et al., 2017; Teixeira et al., 2015). Thus, the aim of this study was to investigate the correlation between the elastic modulus obtained from ultrasonic testing and the modulus obtained through a simple unconfined compaction test on clay soil specimens compressed at different moisture content.

2. Materials and Methods

2.1. Soil characterization and compaction

Deformed samples were collected from the deposits available in the region of Limeira (São Paulo, Brazil), a characteristic soil of the region (Fig. 1). The choice of deposit considered an area with minimum traffic of people where there was no need for deep excavations, guaranteeing the homogeneity of the material. After extraction, the sample was sieved and prepared (ABNT, 2016a) for characterization according to grain size distribution test (sieving and sedimentation) (ABNT, 2016b) and density.

To define the optimum moisture content and the maximum dry unit weight of the samples, we performed compaction tests using the Proctor method at normal compaction energy (ABNT, 2016c). Then, we molded specimens at 2% below the optimum moisture content (A1), at the optimum moisture content (A2), and 2% above the optimum moisture content (A3). Five cylindrical specimens (diameter 100 mm, height 127 mm) were molded for each moisture content and for each storage condition (packed and unpacked), totaling 30 specimens. All samples were exposed to the environment conditions of the laboratory for 120 days.

2.2. Ultrasonic testing

The nondestructive ultrasonic testing was performed 120 days after molding using the Epoch4 equipment (Panametrics, USA) with 500 kHz frequency transducers capable of measuring longitudinal and transverse waves. The compressional ($V_p$) and shear ($V_s$) velocities were calculated through the relation between the distance traveled by the wave ($d$), in millimeters, and the time of the course ($t$), in microseconds. In the tests with the shear transducer, a coupler gel (corn glucose) was required to minimize reflection and refraction of ultrasonic pulse. The aim of the ultrasonic testing was to determine the elastic modulus of the samples to compare with the results obtained from the destructive method (compression test).

$$V = \frac{d}{t}$$

(1)

2.3. Determination of the elastic modulus by ultrasonic test

The stiffness matrix (Eq. 3) was determined using the longitudinal ($V_p$) and shear ($V_s$) velocities and considering the soil as an isotropic material, where the parameters of the diagonal ($C_{ii}$) $C_{11} = C_{22} = C_{33}$ were calculated using an average of the $V_p$ and likewise $C_{ii} = C_{ii} = C_{ii}$ and using an average of the $V_s$ (Eq. 2).

Through the inverse of stiffness matrix, the flexibility matrix (Eq. 4), we can determine the longitudinal elastic modulus ($E_{long}$) using the nondestructive ultrasonic testing (Eq. 5). Other elastic constants, such as the shear modulus ($G_s$) and Poisson’s ratio ($\nu_{s}$), can be determined using the matrices, $S_{ii}$ and $S_{ij}$, respectively; however, this was not the focus of this study.

$$C_{ii} = \rho V_p^2$$

(2)
Christoffel (Bucur, 2006) developed the theoretical equations above and these have already been applied for wood by other researchers (Gonçalves et al., 2011b, 2014; Kohlihauser & Hellmich, 2012; Vázquez et al., 2015), in concrete (Gonçalves et al., 2011a) and stabilized soil (Ferreira et al., 2013; Hoffmann & Gonçalves, 2010; Milani, 2008).

2.4. Determination of the elastic modulus by compression test

After the ultrasonic test, the specimens were subjected to unconfined simple axial compression tests by the press EMIC 23-600 of the brand INSTRON/EMIC (Fig. 2), with deflection control to determine the static elastic modulus ($E_{st}$). The method used was adapted according to the standards of resistance to unconfined compression of cohesive soils and elastic modulus of concrete (ABNT, 1992, 2008).

To validate the results between the moduli obtained by ultrasonic and by static testing, statistical tests (linear regression, confidence interval, t-test) were performed using the Origin 8.1 software to determine if there is a statistically significant correlation between the analysed variables.

### Table 1 - Casting conditions based on moisture content.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Optimum moisture content (%)</th>
<th>Dry unit weight (kN.m$^{-3}$)</th>
<th>Porosity (%)</th>
<th>Voids ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>21.40</td>
<td>15.14</td>
<td>43</td>
<td>0.76</td>
</tr>
<tr>
<td>A2</td>
<td>23.40</td>
<td>15.89</td>
<td>40</td>
<td>0.68</td>
</tr>
<tr>
<td>A3</td>
<td>25.40</td>
<td>15.68</td>
<td>38</td>
<td>0.61</td>
</tr>
</tbody>
</table>

As shown in the particle size curve (Fig. 3), the soil used was classified as ML, according to the Unified Soil Classification System (USCS), composed of 55% clay, 23% sand and 22% silt, with a specific weight of the solids equal to 27.9 kN.m$^{-3}$.

The results of optimum moisture content and maximum dry unit weight used to mold the specimens were obtained from the compaction curves. The specimens were molded according to the moisture conditions described in Table 1, 15 of them were packed and 15 exposed to laboratory air for 120 days.

The increase in compaction energy results in a decrease in the macroscopic and microscopic pores of granular materials (Caputo, 1988; Pinto, 2006) and the velocity can vary according to the propagation medium and the presence of voids. Due to this, it was decided to analyze the three compaction energies of the Proctor method (ABNT, 2016c). Mansour et al. (2016) points out that the variation in porosity and voids can interfere with the application of acoustic methods of investigation applied to compacted soil.

The purpose of the two types of storage (packed and unpacked) was to qualify the velocity differences of specimens with variations of moisture and density. Thus, we verified an average loss of approximately 17.0% in moisture and 17.0% in density in the unpacked specimens, in contrast to 2.9% and 2.6%, respectively, in those that remained packed, after 120 days.
3.2. Nondestructive testing

The final velocities obtained for the packed specimens were lower than on the exposed specimens by approximately 20% for longitudinal to compressive wave velocities \( (V_p) \) and 26% for shear wave \( (V_s) \) velocities. This behavior was expected due to the moisture content presence, which increases the dispersion of the ultrasonic pulse (Bernat-Maso et al., 2017; Luong et al., 2014). Additionally, we can consider the occurrence of a thixotropic behavior, which may increase the resistance in clayey samples with a high degree of saturation when kept at rest (Jeong et al., 2015; Seng & Tanaka, 2012).

The \( V_p \) values obtained in this study ranged between 891 and 1407 m.s\(^{-1}\) (Figs. 4a and 5a), for the packed and unpacked specimens, respectively, and agree with values found in the literature. Studies that use soils classified as sandy are usually more common, with \( V_p \) located between 954 and 1376 m.s\(^{-1}\) (Ferreira et al., 2013; Hoffmann & Gonçalves, 2010; Milani, 2008; Sarro et al., 2015). For clayey and compacted soils at intermediate energy (the same used in this research), Teixeira et al. (2015) obtained a mean \( V_p \) of 1444 m.s\(^{-1}\). Sarro et al. (2017) used normal compaction energy and obtained mean values of approximately 1500 m.s\(^{-1}\).

Regarding \( V_s \), we obtained values between 491 and 837 m.s\(^{-1}\) (Figs. 4b and 5b), for the packed and unpacked specimens, respectively. There is not enough data on this type of velocity due to the lack of research on the application of ultrasonic testing in soil. Hoffmann & Gonçalves (2010) obtained mean values of 502 m.s\(^{-1}\) for samples of sandy soil molded at normal energy and kept in moist environment for seven days, while Milani (2008) obtained average \( V_s \) of 810 m.s\(^{-1}\) for stabilized soil with 7% Portland cement. Wang et al. (2006) studied frozen soil samples and obtained higher \( V_s \) values than other authors (mean of 1120 m.s\(^{-1}\)). This behavior is expected due to increased water viscosity with decreasing temperature, which reduces the velocity of wave propagation (Bucur, 2006; IAEA, 2002).

Figure 3 - Soil particle-size distribution.

Figure 4 - Comparison between \( V_p \) (A) and \( V_s \) (B) of each condition for the unpacked specimens.
The high variation in the values of $V_S$ and $V_P$ is due to the storage difference of the samples. In the packed specimens, the velocities were lower because of the higher moisture content. This effect was also observed by Sarro (2017) and Sarro et al. (2017) when comparing samples with different moisture content. In addition, the presence of water in the pores of the material may still result in a decrease in the ultrasonic wave amplitude (Bernat-Maso et al., 2017; Mansour et al., 2016; Markov et al., 2014).

When comparing the three moisture conditions of the unpacked specimens analyzed through Student’s t-test and ANOVA, conditions A2 and A3 are statistically equal (p-value = 0.00), the only condition that showed same statistically significant difference was A1 (Fig. 4). Although these specimens lost moisture to the environment during the same period (120 days), the variations in compaction moisture caused differences in the microstructure. The ultrasonic testing identified this microstructural difference, which is more significant when moisture is above the optimum (Andrianatrehina et al., 2018; Otálvaro et al., 2015; Romero, 2013).

Regarding the specimens that were packed, the velocities of the three moisture contents presented significant statistical difference (Fig. 5). This difference is caused by the higher water content, which differentiates the soil microstructure (Otálvaro et al., 2015). This behavior corroborates the assertion that moisture content is the factor that most influences velocity (Sarro et al., 2017; Teixeira et al., 2015).

The longitudinal moduli obtained by ultrasonic testing ($E_u$) (Fig. 6) on the exposed specimens was higher than on the packed specimens by 32%, which had a higher coefficient of variation ($\text{CV} = 15\%$; 32% and 7% for A1, A2 and A3, respectively) due to the greater water content. Moreover, for the unpacked specimens, the modules were considered statistically equal for the A2 and A3 condition, while for packed specimens the three moisture content conditions were statistically different.

The elastic moduli were higher in unpacked test bodies due to partial loss of moisture, causing the suction effect. According to literature, the modulus of elasticity in clay soils is influenced directly by the degree of saturation and suction, being this parameter higher in soils with lower moisture content (Adem & Vanapalli, 2015; Vanapalli & Adem, 2014).

Furthermore, the velocity is influenced directly by the moisture content, as verified in other researches (Bui et al., 2014a; Cardoso et al., 2017; Champiré et al., 2016; Chen et
al., 2017; Dongqing et al., 2016; Sarro et al., 2017), being higher in specimens with lower moisture content. Therefore, since the EUS is calculated from the velocity, the value of the modulus being higher for these specimens was expected.

We compared our results for the modulus with results from the literature to highlight the importance of this study (Table 2).

The elastic modulus obtained by ultrasonic testing for unpacked specimens (Fig. 6b) presented similar values to those obtained by Wang et al. (2006) and Christ & Park (2009), being 2.75 and 2.5 GPa, respectively. However, these authors used frozen materials in their research. Other authors found in the literature cannot be compared with this research because they studied a different type of soil (sandy).

The values obtained by Bui et al. (2014a) were lower than those obtained by other authors for the modulus of elasticity, the behavior was similar to that of the present study, where the modulus was higher for unpacked (dry) samples than for packed (wet) samples.

3.3 Mechanical characterization

Unpacked specimens presented greater compressive strength (Fc) when compared with packed specimens (Fig. 7). A possible explanation for this is that soils with higher saturation have lower resistance (Caputo, 1988; Pinto, 2006). Teixeira et al. (2015) and Bandeira (2009) also observed this behavior, their research having been performed on sandy and clayey soil, respectively. Ferreira & Freire (2005) used silty soil and obtained a compressive strength of 2.60 MPa.

The static elastic modulus (Est) (Fig. 8) presented the same behavior as those obtained by ultrasonic testing (Fig. 6a), i.e., the values of unpacked specimens were ap-

Table 2 - Summary of elastic modulus values obtained by other authors.

<table>
<thead>
<tr>
<th>Author</th>
<th>Material</th>
<th>Elastic Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nondestructive testing ( (EUS) )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ferreira et al. (2013)</td>
<td>Sandy</td>
<td>1.66</td>
</tr>
<tr>
<td>Hoffmann &amp; Gonçalves (2010)</td>
<td>Sandy</td>
<td>1.14</td>
</tr>
<tr>
<td>Christ &amp; Park (2009)</td>
<td>Silty</td>
<td>2.50</td>
</tr>
<tr>
<td>Milani (2008)</td>
<td>Sandy (soil-cement)</td>
<td>5.70</td>
</tr>
<tr>
<td>Wang et al. (2006)</td>
<td>Clayey</td>
<td>2.75</td>
</tr>
</tbody>
</table>

| Destructive testing \( (EST) \) |                      |                       |
| Champiré et al. (2016) | Sandy | 1.20-2.80 |
| Lombillo et al. (2014) | Sandy | 0.36 |
| Bui et al. (2014a) | Sandy | 0.58-0.18\textsuperscript{1} |
|                         |       | 0.95-0.39\textsuperscript{1} |
| Miccoli et al. (2014) | Sandy | 2.20 |

\textsuperscript{1}For 2% and 11%, respectively, of sand-silt soil.

For 3% and 8% moisture, respectively, of a silt-clay soil.
proximately 55% greater than those exposed. However, $E_{ss}$ (Fig. 6a) and $E_{us}$ (Fig. 8) showed similarities, with values between 1.25 and 2.50 GPa.

Miccoli et al. (2014) determined the static modulus of mini-walls of compacted soil blocks and obtained $E_{ss} = 2.2$ GPa. Although we used a different soil from that research (sandy), the values are within the same range. Champiré et al. (2016) studied specimens molded with three types of sandy soil and obtained values between 1.2 and 2.8 GPa.

We must emphasize that the values found in the literature are very different from those mentioned above, which is due to the plastic behavior of the soil and the conditions of the test. Although the results of Bui et al. (2014a) are not consistent with our results, the behavior observed by the author was the same, the modules being greater for dry specimens when compared with moist specimens.

Therefore, the need for research in this area is evident, considering the scarcity of elastic modulus values for both destructive and nondestructive tests.

### 3.4. Statistical analysis

The correlation coefficients ($R$) between compressive strength ($F_c$) and static elastic modulus ($E_{ss}$) were high for both storage conditions, with $R$ equal to 0.97 and 0.99 for the unpacked and packed condition, respectively (Table 3).

In this case, the static modulus of the unpacked condition is directly proportional to the increase in resistance. For the packed condition, it is inversely proportional.

The same occurs when the static and ultrasonic modules are correlated, with $R$ equal to 0.98 for both storage conditions, being directly proportional for the unpacked specimens and inversely proportional for the packed specimens. This behavior is consistent since the modulus, as well as velocity, tends to be smaller the greater the moisture content.

### 4. Conclusion

The ultrasonic testing allows to infer resistance and elasticity properties of compacted soil, considering the high correlations obtained between these parameters. Nevertheless, to validate the use of the technique in determining the elastic constants as a whole, including the shear modulus and Poisson’s ratio, it is necessary to obtain these parameters with triaxial tests, verifying the correlation between them.

Further study is required on the influence of moisture in the ultrasound test, since this factor directly influences the mechanical behavior of the material when compacted. Even so, the test allowed us to detect differences in moisture in specimens, indicating the potential of the technique in compaction control.
Acknowledgments

The authors thank Espaço da Escrita - Coordenadoria Geral da Universidade - UNICAMP - for the language services provided.

References


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Equipamentos, Abendi, Porto de Galinhas, PE, available in CD-ROM.


