CORRELATIONS BETWEEN DYNAMIC AND STATIC MECHANICAL PROPERTIES OF CLAYEY SOILS

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ABSTRACT

Static Parameters of soil such as the Static Elastic modulus ($E_s$) and the Unconfined Compressive Strength (UCS) are important parameters used to predict the behavior of soil under static load. However, the tests to obtain such parameters are time-consuming and destructive. By correlating the static parameters to the dynamic ones, one can use a nondestructive method such as the ultrasonic test to predict the needed parameters. This study presents the results of experiments conducted on clayey soil samples in the aim of investigating possible correlations between their mechanical properties and ultrasonic pulse velocities of Primary wave and Shear wave. Uniaxial Compression and ultrasonic tests were carried out on 20 clayey soil samples retrieved by wash coring from different sites. A regression analysis was done to find the best fit equations for predicting the static parameters of the tested clay. The obtained equations provide high correlation coefficients and can be used to predict certain parameters (modulus of elasticity, shear modulus and unconfined compressive strength) with acceptable accuracy.

Key words: Young’s modulus, shear modulus, wave velocity, dynamic modulus, soil, clay, ultrasonic, pulse velocity, unconfined compressive strength

Cite this Article: Mohammad Traboulsi and Riad Al Wardany, Correlations between Dynamic and Static Mechanical Properties of Clayey Soils, International Journal of Civil Engineering and Technology, 10(01), 2019, pp. 2602–2612

http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=10&IType=01
1. INTRODUCTION

In nature, soils exist in a state between being completely dry or fully saturated. The strength, deformation, permeability and other mechanical properties of soils depend on many factors such as the shapes of particles, interaction between grains, void ratio and degree of saturation. Knowing these factors is important to understand the behavior of soils under different conditions. The elastic properties of soils determine how much the soil can compress under a given load. Obtaining such properties has interested the geologists as well as the seismologists for many decades and there is still an interest to improve the methods used to obtain and analyze these parameters. However, calculating the elastic properties of clays is usually highly problematic since clay is a highly nonlinear material with very low yield strains. Destructive and non-destructive methods often fail to provide deformations below 0.01% strain which is the range of elastic deformation in clay. In situ geophysical methods as well as laboratory tests that use propagation of elastic waves allow for the measurement of stiffness parameters with very low strains. Elastic wave based methods provide two important stiffness parameters (E_max and G_max). The two parameters have important applications regarding understanding the soil behavior under seismic loading. First, it is possible to predict the effect of soil parameters such as (particle size and shape, moisture content, stress history, cementation etc...) on the soil behavior which was done in several studies (Yesiller, Inci, and Miller (2000), Foti and Lancellotta (2004), Hardin and Drnevich (1972)). In addition, during site characterizations, elastic wave propagation allows providing a better insight into the conditions of the strata and the potential problems that may be encountered in the site. Although Many studies have been reported on the investigation of small-strain shear modulus (G_max) due to its applications in determining settlement and understanding soil behavior under dynamic loading, few studies have been conducted on the small strain young’s modulus and its relation to the static moduli (Payan et al. 2016). Young’s modulus is needed in many applications in the field of geotechnical engineering. On one hand, the small-strain Young’s modulus is important in determining the settlement of buildings subjected to dynamic loading such as wind and seismic loadings. On the other hand, the static Young’s modulus characterized by the secant modulus (E_sec) and the tangent modulus (E_t) provides an insight into the behavior of shallow and deep foundations as well as retaining structures. For that, a relationship between the dynamic and static moduli is vital.

2. LITERATURE REVIEW

Early studies correlated ultrasonic wave velocities, and consequently the small-strain stiffness, with the density of the material. P-wave velocities and dry densities followed a similar trend with respect to water content where the peak value was obtained within ±0.5% (Sheeran, Baker, and Krizek 1967; Yesiller, Inci, and Miller 2000). Wang et al. (1991) conducted a study to correlate water content and pressure in silt with P-wave velocity. Several researchers showed that elastic waves can be correlated with the material stiffness, particle size and cementation (Goddard 1990; Ghayoomi, Suprunenko, and Mirschekari 2017; Sawangsuriya 2012). Later, researchers correlated small-strain stiffness with soil compressibility and soil fabric (Cha et al. 2014; Byun et al. 2013). Foti and Lancellotta (2004) tested an equation for the estimation of soil porosity from elastic wave velocities. Stress waves have also been correlated with plasticity and clay content. Yesiller, Inci, and Miller (2000) showed that compression wave velocities are inversely proportional to clay content and plasticity. However, it has been showed that there is poor correlation between the ultrasonic pulse wave velocities and Atterberg limits (Sawangsuriya, 2006). Other researches presented several successful attempts in correlating P-wave velocity with different factors; Wei and Huang (2017) showed that the average P-wave
velocity has a nonlinear decrease rate with the increase of drying-wetting cycles under constant water content and amplitude. Zhang and Bentley (2005) investigated the relationship between the static Poisson’s ratio and the dynamic Poisson’s ratio (that can be obtained from stress waves). In general, the behavior of stress waves depends on the properties of the material in which they propagate. Sawangsuriya (2006) stated that these waves depend on several parameters including the effective stress, void ratio, cementation and stiffness of the mineral, water and air phases, type of soil and stress history. However, shear wave velocity is affected primarily by density, void ratio and effective stress (Hardin and Drnevich 1972).

3. SPECIMENS

A total of twenty samples of clayey soils were gathered from different sites in Lebanon and tested in this study. The used clay is described as a lean clay (CL) according to ASTM 2488. The samples were taken from boreholes by wash drilling method; this is to assure a better preservation of the sample compactness, the stress history and the in situ soil strength which are the main factors affecting soil mechanical moduli. The samples were cut in the laboratory from the retrieved cores and were prepared for testing; the height to diameter ratio of all samples was kept between 2 and 2.5. The range of characteristics for the samples is provided in Table 1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (D, cm)</td>
<td>6.5 – 7.5</td>
</tr>
<tr>
<td>Height (h, cm)</td>
<td>13 – 15</td>
</tr>
<tr>
<td>Unit weight (γ, kN/m³)</td>
<td>17.8 – 22.19</td>
</tr>
<tr>
<td>Water content (w, %)</td>
<td>5.89 – 24.31</td>
</tr>
</tbody>
</table>

4. EXPERIMENTAL PROGRAM & DATA PROCESSING

P-wave and S-wave velocities were measured on the tested samples through direct transmission using a commercial specialized ultrasonic testing machine. Each wave was identified with the help of time-frequency analysis, and its time of arrival was measured. The velocity was calculated by dividing the distance traveled by the wave, which is in the current case the height of the specimen, divided by the measured time. Calibration of the sensors and the measurement setup was conducted at the beginning of the tests and the time delay was removed. The transducers used in the experiments were piezoelectric transducers; their resonance frequency was 100 kHz with an optimum sensitivity that ranges between 1 and 30 kHz. The type of the generated pulse was Tone Burst, and the level of gain was fixed at 60 dB. Figure 2 shows a schematic diagram of the test setup.
In order to improve the signal-to-noise ratio, each wave was measured by averaging each signal 30+ times. In addition, an ultrasonic petroleum coupling agent was used to improve the surface contact between the transducers and the surface of the sample. The signals were then filtered using a low-pass filter and the arrival time was obtained using the STA/LTA algorithm proposed by (Allen 1982). For that, a spectrogram is created by calculating the short-time Fast Fourier Transform (FFT) of within a specific interval, then the FFT window is moved along the axis of time. The gathered processed data is then presented in the time-frequency domain; an example is presented in Figure 5.
Figure 5 Example of time-frequency analysis with the identification of P and S waves

The STA/LTA method utilizes an index which is the ratio between the short-term average and the long-term average. Mathematically, this method can be written as (Chi-Durán et al. 2017):

\[
S^{STA}(t) = \frac{1}{T^{STA}} \sum_{j=t-T^{STA}}^{t} s(j)^2
\]

where \( T^{STA} \) is the size of the short window,

\[
S^{LTA}(t) = \frac{1}{T^{LTA}} \sum_{j=t-T^{LTA}}^{t} s(j)^2 t
\]

and \( T^{LTA} \) is the size of the long window. Thus, the STA/LTA ratio:

\[
S(t) = \frac{S^{STA}(t)}{S^{LTA}(t)}
\]

The short time average window measures the instant value of the signal. In general, it should be longer than 1 instant to remove the effect of noise or reflections. However, the STA should not be very long so as not to be influenced by the period of the signal. In essence, the STA is a function filter. If it is too short, the filter is too sensitive to the change and if it is too long it no longer provides value. The LTA window measures the average amplitude of a period of the signal. It should be longer than the STA window. By changing the LTA window duration, the recording can be more or less sensitive to the regional events (TMKOCZY 1999).
Figure 6 Example of STA/LTA method used to obtain the arrival times of P (at 435.5 μs) and S (at 737.5 μs) waves. From top to bottom: unfiltered signal, filtered signal, average spectral density, STA/LTA ratio and triggers.

Once the time of arrival of each wave is determined, the corresponding velocity can be calculated. The dynamic modulus is thus obtained by the following relation:

\[ E_d = \rho V_p^2 \frac{3V_p^2 - 4V_s^2}{V_p^2 - V_s^2} \]

where \( \rho \) is the bulk density and \( V_p \) and \( V_s \) are the P-wave and S-wave velocities respectively.

The static parameters of the specimens were obtained using the unconfined compression test (provided in ASTM D2166). The test provides 2 main parameters: the unconfined compression strength \( q_u \), which can provide the ultimate shear strength at saturation: \( c_u = \frac{q_u}{2} \), and the static young’s modulus. In the current study, a distinction was made between the secant modulus and the tangent modulus of the tested clay.

5. RESULTS & DISCUSSION

The static parameters obtained from the unconfined compression test were correlated with the dynamic elastic modulus and wave velocity using linear and non-linear regression. The best fit equation with 90% confidence limit, and the correlation coefficient \( r \) were determined for comparison.

The Unconfined Compressive Strength (UCS) was correlated with \( E_d \) with a strong correlation coefficient \( (r = 0.935) \) using an exponential correlation (Figure 7). A better relation to obtain \( q_u \) is to multiply it by the bulk density \( \rho \). Evidently, the exponential relation between
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$\rho \cdot q_u$ and $G$ has a correlation coefficient $r = 0.942$ (Figure 8, where $G$ is the shear modulus defined as: $G = \rho V_s^2$).

![Figure 7](image)

**Figure 7** Correlation between the Unconfined Compression Strength (UCS) and the dynamic elastic modulus $Ed$ (MPa) of the tested samples

![Figure 8](image)

**Figure 8** Correlation between the product of the unit weight $\times$ Unconfined Compression Strength (UCS) and the shear modulus $G$ (MPa) of the tested samples

A linear correlation was found between $E_t$ (measured by the mechanical UCS test) and $E_d$ (calculated from the measured P-wave and S-wave velocities) with a strong correlation coefficient ($r = 0.95$, Figure 9). An improved correlation was found between $E_t$ and $V_p^2 - V_s^2$ which gives a correlation coefficient of $r = 0.963$ (Figure 10).
Figure 9 Correlation between the tangent modulus and the dynamic modulus

![Graph showing correlation between tangent modulus and dynamic modulus]

Figure 10 Correlation obtained between $E_t$ and $V_p^2 - V_s^2$

The highest correlation value for predicting $E_s$ was found with respect to $(\rho V_s)^2$ ($r = 0.9$) using an exponential relation (Figure 11). An improved correlation coefficient was obtained between $\rho E_s$ and $(\rho V_s)^2$ with $r = 0.912$ (Figure 12).
Table 2 Summary of the obtained equations

<table>
<thead>
<tr>
<th>Parameters (y,x)</th>
<th>Equation</th>
<th>a</th>
<th>b</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>qu, Ed</td>
<td>$y = a \exp(b \times x)$</td>
<td>0.2154</td>
<td>1.16x10^{-3}</td>
<td>0.935</td>
</tr>
<tr>
<td>rqu, G</td>
<td>$y = a \exp(b \times x)$</td>
<td>0.4265</td>
<td>3.07x10^{-3}</td>
<td>0.942</td>
</tr>
<tr>
<td>Et, Ed</td>
<td>$y=ax+b$</td>
<td>6.13x10^{-2}</td>
<td>-6.347</td>
<td>0.952</td>
</tr>
<tr>
<td>Et, $V_p^2/V_s^2$</td>
<td>$y=ax+b$</td>
<td>1.62x10^{-4}</td>
<td>-10.224</td>
<td>0.963</td>
</tr>
<tr>
<td>$E_s, (rV_s)^2$</td>
<td>$y=a\exp(b \times x)$</td>
<td>14.13</td>
<td>0.0129</td>
<td>0.900</td>
</tr>
<tr>
<td>$rE_s, (rV_s)^2$</td>
<td>$y=a\exp(b \times x)$</td>
<td>27.972</td>
<td>0.0135</td>
<td>0.912</td>
</tr>
</tbody>
</table>
6. CONCLUSION

This study provides correlations between the static and dynamic mechanical characteristics of clay. As a result, it provides equations to predict the unconfined compressive strength, the tangent static modulus and the secant static modulus from dynamic properties. The results provided serve to provide an insight into the nature of the relation between the small-strain and large-strain properties. The results show that the tangent elastic modulus can be strongly correlated with $E_d$ and $V_p^2 - V_s^2$. The secant modulus is better correlated with the shear modulus or the shear wave velocity. The unconfined compressive strength can be correlated with the dynamic modulus and the shear wave velocity.

ACKNOWLEDGEMENTS

This work was supported by Rafik Hariri University, Lebanon

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