Study of Shear Wave Velocity of Macao Marine Clay under Anisotropic Stress Condition

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ABSTRACT :

Shear wave velocity, V_s of soft clay is an important parameter for seismic resistant design as well as for deformation analysis of earth structures as it is directly related to the very small-strain stiffness. And the measurement of V_s is a critical task in the solution of geotechnical earthquake engineering problems. In this study, piezoelectric bender elements were used to measure the shear wave velocity on reconstituted specimens of soft Macao marine clay. Various initial stress conditions, including isotropic and various stress ratios, η, were simulated in the triaxial apparatus. Two signal interpretation methods, the characteristic peaks and the cross-correlation, were used to determine the travel time for calculation of the shear wave velocity. In addition, void ratio functions were assessed, and empirical correlations between the maximum shear modulus and the initial stress condition as well as the void ratio were proposed for Macao marine clay.

KEYWORDS: shear wave velocity, anisotropic stress, bender element

1. BACKGROUND

Macao is currently a Special Administrative Region of China, situated at the Pearl River Delta of the Guangdong Province. There are three parts of Macao, namely, the Macao peninsula, the Taipa, and the Coloane Islands; the area of the entire region is less than 30 km^2. The geological setting of this area is rather simple. A large portion of the region is from land reclamation. The general soil profile is a layer of fill covering the marine deposit, followed by alluvium of alternating sand and silty clay which overlies the completely decomposed granite and the bedrock. The layer of marine deposit is typically normally consolidated, whose properties are important to local engineering practice. Due to rapid economical growth, there are many infrastructures under construction in Macao. Although there are many tests performed on the engineering properties of the Macao marine clay, the results are usually related to static loading condition. The dynamic behavior of the soils in Macao, in particular the marine clay, is not well investigated.

2. MEASUREMENT OF SHEAR WAVE VELOCITY

Shear wave velocity, V_s of marine clay is an important parameter for seismic resistant design of infrastructure. In addition, the very small-strain shear modulus, G_{max}, which is also crucial for deformation analysis of earth structures under static loading, is directly related to V_s. Since the dynamic behavior of Macao marine clay is not well investigated, the main objective of this study is to investigate the variations of V_s under anisotropic stress condition for Macao marine clay and to develop an empirical expression of G_{max} for preliminary design.

In this study, bender element technique is chosen for determining V_s and this technique was pioneered by Shirley & Hampton (1977). For measurement of V_s, a pair of bender elements is used whereby one of the bender elements is used for transmitting a signal, called transmitter and the other called receiver. Figure 2.1 shows the typical setup of bender element testing system. By measuring the travel time of shear wave, V_s can be determined by the following expression (Dyvik & Madshus 1985; Viggiani and Atkinson 1995; Brignoli et al. 1996):

$$V_s = L/t \tag{2.1}$$

where L is the tip-to-tip distance between the two bender elements, and t is the travel time of the shear wave. From the theory of elastic wave propagation, G_{max} can be determined as

$$G_{max} = \rho (V_s)^2 \tag{2.2}$$

where ρ is the bulk density of the soil specimen. Four methods have been suggested by Arulnathan et al. (1998) for determination of V_s. They are first direct arrival time, second arrival time, travel time between characteristic peaks and cross-correlation of input and output signals. In this paper travel time between characteristic peaks and cross-correlation methods are used for determination of V_s. Details of these two methods are described by Viggiani and Atkinson (1995) and Arulnathan et al. (1998).

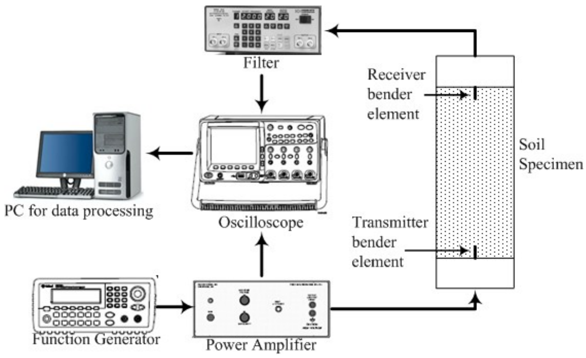

Figure 2.1 Typical setup of bender element testing system

According to Roesler (1979), Yu and Richart (1984), Stokoe, Lee and Knox (1985) and Lee (1985), it is possible to express G_{max} (or G_{ij}) by means of the following empirical relationship:

$$G_{ij} = S_{ij} F(e) p_a^{1-ni-nj} (\sigma_i^{'})^{ni} (\sigma_j^{'})^{nj} \tag{2.3}$$

where G_{ij} =elastic shear modulus in the i-j plane; S_{ij} =material constant; F(e) =void ratio function; σ'_i and σ'_j=effective stresses acting on the plane in which G_{ij} is measured; ni, nj =empirical exponents for σ'_i, σ'_j, respectively, ni is usually equal to nj for sand; Pa = atmospheric pressure. Although Equation 2.3 is widely accepted, many researchers published different void ratio functions; Table 2.1 summarized some of them. The void ratio function used in this study can be expressed as:

$$F(e) = \frac{[f(e)]^2 (G_s - e)^2}{1 + e} \tag{2.4}$$

where e= void ratio; G_{ij} =specific gravity of the soil; f(e) =void ratio function taken as e^{λ} in this study.

3. TESTING EQUIPMENT AND MATERIALS

3.1. Testing Equipment

Figure 3.1 shows the automated triaxial testing system (Li et at. 1988) used in this study. Triaxial top and bottom platens were modified in order to install bender elements. A pair of bender elements was inserted into the specimen at both ends to determined the shear wave velocity. Figure 3.2 shows the equipment for recording input and output signals, including a power amplifier, a function generator, a filter and an oscilloscope.

Table 2.1 Various published expression of void ratio function

Reference	Void ratio function
This study	$e^{2\lambda}(G_s + e)^2/(1+e)$
Hardin and Richart (1963)	$(2.17 - e)^2/(1+e)$
Hardin and Black (1968)	$(2.91 - e)^2/(1+e)$
Marcuson and Wahls (1972)	$(4.4 - e)^2/(1+e)$
Shibata and Soelarno (1978)	$0.67 - e/(1+e)$
Kokusho et al. (1982)	$(7.32 - e)^2/(1+e)$
Shibuya and Tanaka (1996)	$e^{-1.5}$
Shibuya et al. (1997)	$(1+e)^{-2.4}$

Figure 3.1 Auto triaxial testing system

Figure 3.2 Equipment for recording input and output signals

3.2. Index properties

In this study reconstituted sample was prepared using a consolidometer. First of all, disturbed sample was mixed with salty water to reach a water content about twice the liquid limit. Then the clay slurry was poured into the consolidometer and loaded to a net effective vertical consolidation stress of approximately 70~80 kPa, the vertical stress was maintained constant until primary consolidation finished. Typical size of reconstituted sample was 200 mm in diameter and about 160 mm in height. Individual triaxial specimens were obtained by quartering and trimming the larger reconstituted sample in to specimens of 38mm in diameter and 76 mm in height. Table 3.1 presents a summary of index properties of the reconstituted specimens used in the triaxial tests together with the values presented by Carter (2001). Most values of the parameters agree with Carter (2001).

Table 3.1 Index properties of reconstituted Macao marine clay

Properties	This study	Carter (2001)
Specific gravity	2.74	n/a
Void Ratio	1.62	1.8~2.0
Water Content (%)	59.16	60~75
Liquid Limit	68	60~75
Plastic Limit	34	30~35
USCS classification	CH	n/a

4. EXPRIMENTAL PROGRAM

Two different categories of tests were conducted to study the variation of shear wave velocity, including constant stress ratio tests and isotropic loading and unloading tests. In this study, mean effective stress, p', deviator stress, q, and stress ratio, η, are defined as

$$p' = (\sigma_a^{'} + 2\sigma_r^{'})/3 \tag{4.1}$$

$$q = \sigma_a^{'} - \sigma_r^{'} \tag{4.2}$$

$$\eta = q/p^{'} \tag{4.3}$$

Where $\sigma_a^{'}$ and $\sigma_r^{'}$ are axial and radial effective stress.

4.1. Constant stress ratio tests

Specimens were anisotropically consolidated from an estimated mean effective stress (p' = 80 kPa) to a mean effective stress of 400 kPa (Series B, C, D in Figure 4.1). The stress ratio, η, during the anisotropic consolidation was -0.3, 0.3 and 1, corresponding to series B, C and D, respectively. Shear wave velocities were measured at the stress states shown in Figure 4.1.

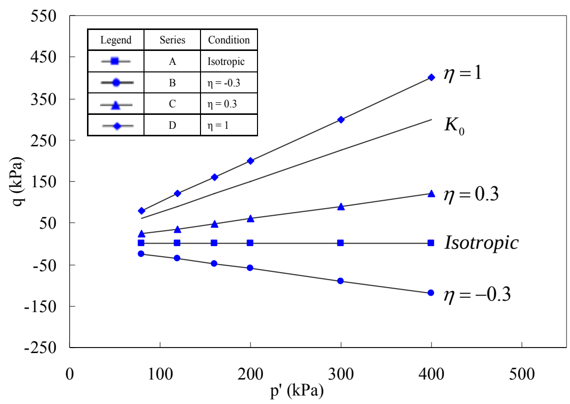

Figure 4.1 Stress paths and stress states for measuring shear wave velocity

In a drain test, loading rate has to be slow enough so that no excess pore water pressure is generated. The rate of change of p' is 2 kPa/hour when p' is less than 200 kPa, 5 kPa/hour when p' is larger than 200 kPa. Shear wave velocity measurements were taken after p' reached the target pressure and primary consolidation finished.

4.2. Isotropic loading and unloading test

The effects of void ratio change on shear wave velocity and shear modulus were studied. The specimens were subject to a number of cycles of isotropic loading and unloading to obtain different void ratios at a specified mean effective stress for reconstituted specimens as shown in Figure 4.2. When a cycle started, specimen was loaded to a specified stress state and shear wave velocity was measured (Figure 4.2 Series A). Then specimen was unloaded to 80kPa of mean effective stress and shear wave velocity was measured again (Figure 4.2 Series E). The shear wave velocities determined under the same isotropic stress level (Series E) were plotted against the corresponding void ratio and the data was used to derive the void ratio function.

The isotropic tests were performed under stress-control with loading rate of 5 kPa/hour in p' for both loading and unloading. Shear wave velocity measurements were taken after p' reached the target pressure and primary consolidation was completed.

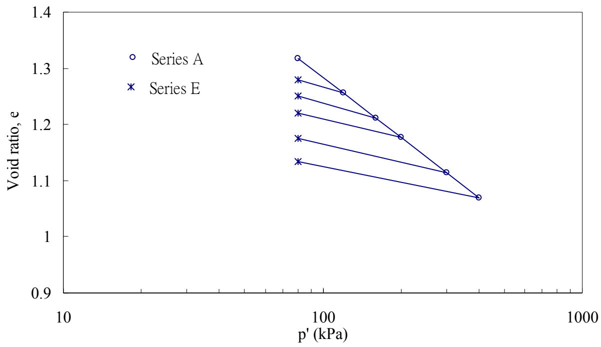

Figure 4.2 Shear wave velocity measurement points (consolidation curve just for illustration)

4.3. Bender element tests

Bender element test was conducted after consolidation finished. As Figure 4.1 and Figure 4.2 showed, shear wave velocity was measured at each point in corresponding series. In this study, 9-mm-wide by 0.58-mm-thick bender elements were installed in the top cap and base pedestal. The bender elements are inserted 2.5 mm into the soil specimen. A single-pulse sinusoidal wave with peak-to-peak voltage of 1.5 V and -90° phase was generated by a function generator as an input signal. Amplifier was set at 10 times. Characteristic peaks and the cross-correlation methods were used for determining the travel time, t, (Viggiani and Atkinson 1995; Arulnathan et al. 1998). Shear wave velocity can then be calculated by using Equation 2.1. Figure 4.3 shows the typical results of these two methods. Travel time equal to 0.4455 ms is obtained by calculating time difference between two peaks of input and output signals, as shown in Figure 4.3(a). The cross-correlation result of input and output signals is shown in Figure 4.3 (b) and normalized with respect to the maximum absolute value, max(CC_{xy}). The time shift corresponding to the maximum of the cross-correlation function is 0.445 ms. The values of travel time obtained from there two methods are very similar, and the value from cross-correlation method was chosen as the final result in this study.

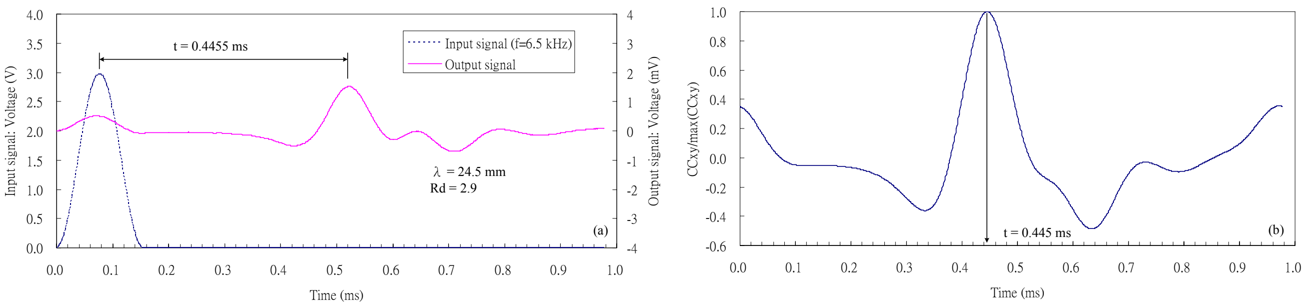

Figure 4.3 Typical signal interpretation results (a) characteristic peaks method (b) cross-correlation method

5. TESTING RESULTS AND DISCUSSION

5.1. Shear wave velocity under anisotropic stress condition

It can be observed from Figure 5.1 that shear wave velocities are directly proportional to the mean effective stress with corresponding stress ratio. As mean effective stress increases, consolidation occurs. During consolidation the void ratio decreases and soil particles become denser; thus, shear wave velocities increase. Curves of each series seem to parallel to each other, and increasing values of shear wave velocity are observed with increasing stress ratio at the same mean effective stress. This result is in agreement with many previous studies (e.g. Bellotti et al. 1996; Rampello et al. 1997).

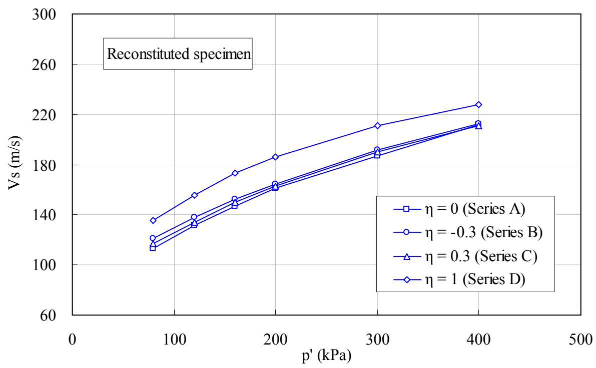

Figure 5.1 Shear wave velocities vs. mean effective stress

Negative constant stress ratio tests for η = -0.3 (Series B) were carried out in this study and a comparison with constant stress ratio tests for η = 0.3 (Series C). As shown in Figure 5.1, shear wave velocities for η = -0.3 are almost the same as that for η = 0.3 at a constant mean effective stress which is also in agreement with Bellotti et al. (1996).

5.2. The void ratio function

From Equation 2.3, shear wave velocity can be evaluated from the current soil stated by means of the empirical expression (Roesler 1979; Belloti et al. 1996):

$$V_{s(ij)} = C_{ij} f(e) \sqrt{p_r^{(1-ni-nj)} (\sigma_i')^{ni} (\sigma_j')^{nj}} = A_{ij} f(e) = A_{ij} e^{\lambda} \tag{5.1}$$

After plotting shear wave velocity, V_s, against the void ratio under constant isotropic confining stress from Series E (Figure 5.2), the empirical exponent of the void ratio function, λ, can be determined by fitting Equation 5.1. The value of λ is -0.88 and R^2 value is 0.9984, respectively.

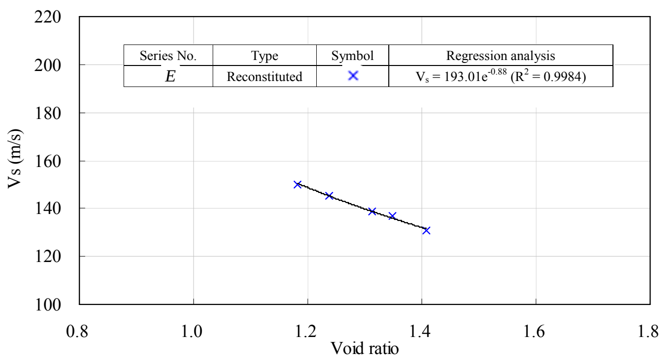

Figure 5.2 Shear wave velocities vs. void ratio at a constant isotropic confining pressure in the series E tests

5.3. Empirical expression for shear modulus

Shear modulus was related to void ratio and the axial and radial effective stresses, as described by the empirical Equation 2.3. Based on the data sets of V_s, e, σ'_a and σ'_r obtained from series A to E, the exponents of Equation 2.3 were obtained by multi-linear regression. The final form is:

$$\frac{G_{max}}{p_a} = 312.53\frac{e^{-1.76}(2.74+e)}{1+e}\left(\frac{\sigma_a^{'}}{p_a}\right)^{0.15}\left(\frac{\sigma_r^{'}}{p_a}\right)^{0.27} \tag{5.2}$$

Exponent of radial stress is larger than that of axial stress for Macao marine clay, which is in agreement with the testing results of Chicago clay published by Jung. Y. H. et al. (2007).

In order to check the accuracy of calculated results, measured values of shear modulus, G_{max}, are plotted against calculated values, G_{cal}, in Figure 5.3, which shows that mean value of G_{cal}/G_{max} for reconstituted specimen is 0.985, with corresponding standard deviation of 0.052. The error of most calculated data are less than ±10%. On the other hand, more measured data in the future may improve the accuracy of the empirical equations.

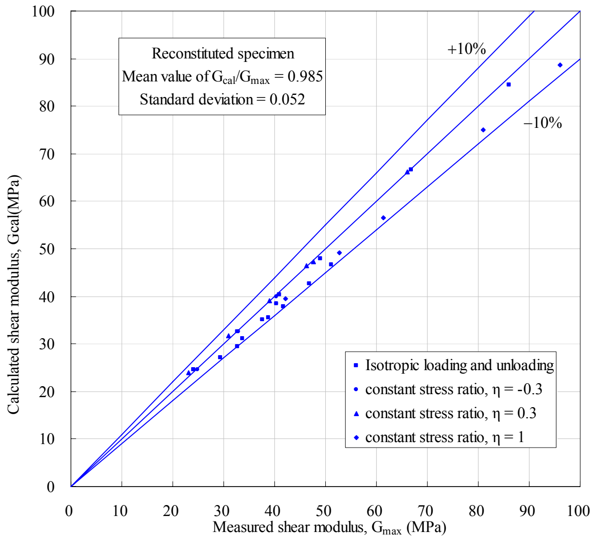

Figure 5.3 Calculated results for reconstituted specimens

6. CONCLUSION

Due to the lack of dynamic behavior of the soils in Macao, a laboratory study was conducted on Macao marine clay to investigate the shear wave velocity and the very small strain shear modulus under different stress conditions. Bender element probes were adopted in the study to measure the shear wave velocity of soils.

Based on the testing results, the values of shear wave velocity are directly proportional to the mean effective stress with corresponding stress ratio; increasing values of shear wave velocity are observed with increasing stress ratio at the same mean effective stress. Negative constant stress ratio tests were carried out in this study. The testing results shows shear wave velocities under a negative stress ratio (e.g. η= -0.3) condition are almost the same as that under a positive stress ratio (e.g. η= 0.3).

The variations in the shear wave velocity at constant isotropic effective stress condition were studied. A void ratio function in the form of f(e) = e^{λ} for shear wave velocity and empirical expression for shear modulus (Equation 5.2) were established. Stress exponents in Equation 5.2 were found to be different for the axial and radial directions.

7. ACKNOWLEGEMENTS

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