Experimental study of variation of shear wave velocity of Macao marine clay during one dimensional consolidation

Étude expérimentale de la variation de vitesse des ondes transversales de l'argile marine de Macao pendant la consolidation à une dimension

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ABSTRACT
The work described in this paper is an experimental investigation on the variation of shear wave velocity of reconstituted Macau marine clay during consolidation using piezoelectric bender elements installed in oedometer. From the results of deformation and the simultaneously acquired shear wave velocity, variation of shear wave velocity during the consolidation process was closely studied. It was found that shear wave velocity drops slightly immediately upon loading, after which it generally increases with the increase of average degree of consolidation. The increase of shear wave velocity reflects the transfer of load from pore water pressure to skeletal stresses during the consolidation process. Based on the experimental results, the relationships between shear wave velocity and vertical effective stress; and between shear wave velocity and void ratio were proposed. These two separate empirical correlations can also be verified with the virgin compression line.

RÉSUMÉ
L'article décrit des recherches expérimentales sur la variation de vitesse des ondes transversales de l'argile marine reconstitué de Macao pendant la consolidation utilisant de languettes piezoelectriques vibrantes installés dans l'oedomètre. Des résultats de la déformation et de vitesse des ondes transversales simultanément acquise, la variation de vitesse des ondes transversales pendant le processus de consolidation a été rigoureusement étudiée. On l'a constaté que la vitesse des ondes transversales chute légèrement immédiatement lors du chargement, après quoi elle augmente généralement avec l'augmentation du degré moyen de consolidation. L'augmentation de vitesse des ondes transversales reflète le transfert de la charge à partir de la pression d'eau interstitielle aux efforts squelettiques pendant le processus de consolidation. Basé sur les résultats expérimentaux, on a proposé les relations entre la vitesse des ondes transversales et l'contrainte effective verticale; et entre la vitesse des ondes transversales et l'indice de vide. Ces deux corrélations empiriques séparées peuvent également être vérifiées avec la ligne vierge de compression.

Keywords : shear wave velocity, marine clay, bender elements test, oedometer

1 INTRODUCTION

The very small strain modulus, G_0, is very important in dynamic analyses such as those used to predict soil behavior under earthquakes, explosions, or machine and traffic vibrations as well as static analyses for many engineering structures (Atkinson & Sallfors 1991; Burland 1989), while the very small strain modulus is directly related to the shear wave velocity, V_s, and the density, ρ, by $G_0 = \rho \cdot V_s^2$ for an elastic material. Therefore, if the variation of V_s in a process can be explored in detail, the corresponding value of G_0 can be determined directly. To investigate the soil modulus at very small strain, advanced laboratory testing, such as the resonant column test, the cyclic triaxial test and the bender element test, can be employed. Among these testing, the bender element test is a simpler and efficient technique and is used to determine shear wave velocity of Macau marine clay in this study.

Bender elements are piezoelectric cantilever beam-shaped transducers capable of generating and detecting shear motion. Many researchers have adopted bender elements to measure V_s in various test equipment. Dyvik & Madshus (1985) measured V_s in resonant column, oedometer, and direct simple shear apparatus; Shibuya et al. (1997) & Fam et al. (1997) measured V_s in oedometer, and Agarwal & Ishibashi (1991) used bender elements in a triaxial cubical box device. In most of bender elements tests performed previously, V_s was usually measured after the full dissipation of excess pore water pressure. Seldom the variation of V_s (or G_0) during the consolidation process has been obtained. In the past several decades, many researchers (Wroth et al., 1985; Hardin et al., 1966; Ni, 1987) have proposed different equations to relate V_s or G_0 to the stress state or void ratio, some taking the effect of unloading and reloading into account together, based on their tests results. In this study, the oedometer was modified to equip with bender elements to measure V_s. The variations of displacement and V_s were monitored during the consolidation process. Empirical equations relating V_s measured after primary consolidation (24 hrs) in the conventional consolidation test to the loading stress (σ_v') and void ratio (e) are proposed for Macau marine clay.

2 TESTING APPARATUS AND PROCEDURES

The investigation was carried out in a modified conventional oedometer device as shown in Fig.1.

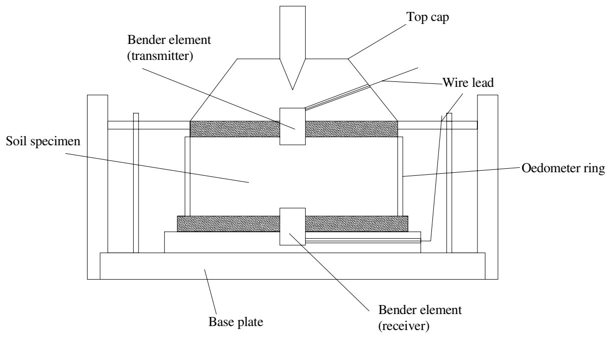

Figure 1. Test set-up of bender element in oedometer

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The shear wave velocity is calculated as $V_s=L/t$, where t is the arrival time and L is the effective travel length of the wave path. In this study, L was taken as the distance between the tips of the bender elements (Viggiani & Atkinson, 1995), which project about 2mm into the specimen. A single sinusoidal pulse with the amplitude of 10V was used as the source. Fig.2 shows typical driving and received signals. The arrival time was interpreted using the peak-to-peak time interval as shown in Fig.2, which was demonstrated by Viggiani & Atkinson (1995) to be similar to the arrival time derived through a numerical analysis of the driving and received signals.

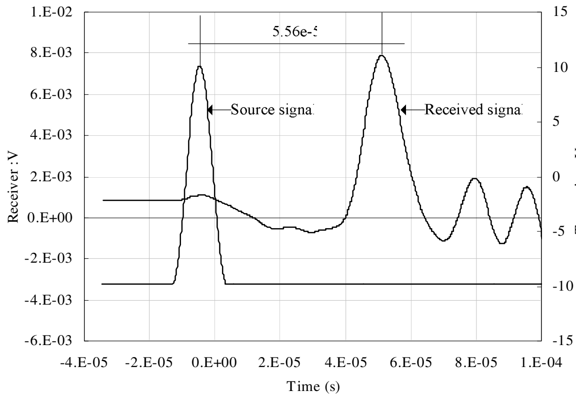

Figure 2 Typical bender elements traces

3 TESTED MATERIALS AND EXPERIMENTAL PROGRAM

Both reconstituted and undisturbed samples were tested in this study (Shi, 2008). However, due to space limitation, only results of reconstituted samples are reported in this paper. Reconstituted samples were prepared by reconsolidation from slurry whose initial water content is about twice the liquid limit. The specific gravity of reconstituted sample is 2.79, while liquid limit and plastic limit are 68% and 34%, respectively. Table 1 summarized the physical and index properties of the reconstituted Macau marine clay samples.

Table 1 Physical and index properties of the reconstituted samples

Sample No.	e_0	γ_s (kN/m^3)	C_c	p'_c (kPa)
G4OMLB03	1.68	16.3	0.49	58
G5OMLB01	1.65	16.4	0.46	55
G6OMLB01	1.63	16.4	0.46	55
G7OMLB01	1.68	16.3	0.51	56

Where e_0 =initial void ratio; γ_s =initial saturation weight; C_c =compression index; p'_c =pre-consolidation pressure

As shown in Table 1, the testing program consists of four tests with reconstituted specimens. The displacement and shear wave velocity were monitored simultaneously in the test G4OMLB03 and G6OMLB01. In the other tests, only the displacements were recorded in the time sequence of 0.1, 0.25, 0.5, 1, 2, 4, 8, 15, 30, 60, 120, 240, 480, 720, 1440 min. and the shear wave velocity was measured after 24 hours of each loading.

4 TEST RESULTS AND DISCUSSION

Fig. 3 shows the relationship between void ratio (e) and vertical effective stress (σ_v') for the reconstituted specimens. Although the four specimens were taken from different batches, they have fair similarity, since they were prepared in the same procedure. In this study, the pressure of 100 kPa was applied to prepare the reconstituted samples every time. The pre-consolidation pressure is less than 100kPa due to the friction between the chamber wall and two o-rings around the loading piston in the consolidometer. As shown in Table 1, the pre-consolidation pressures are in the range of 55-60kPa. Details of the sample preparation were described by Shi (2008).

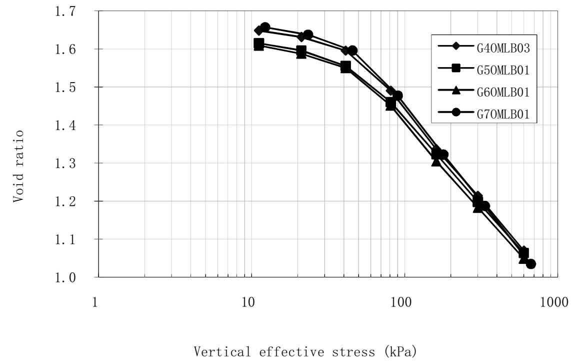

Figure 3 Void ratio vs. loading stress for reconstituted samples

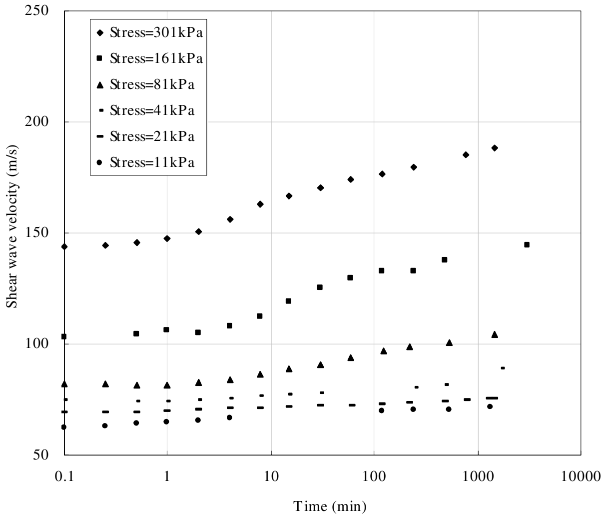

Figure 4 Shear wave velocity vs. time at different loading stages for test G4OMLB03

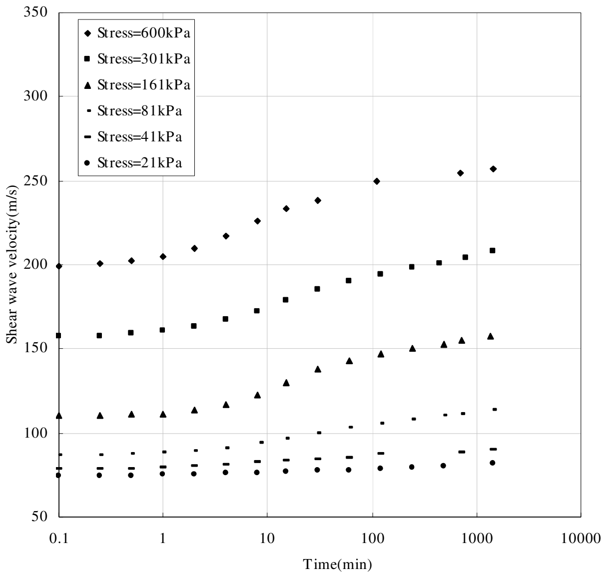

Figure 5 Shear wave velocity vs. time at different loading stage for test G6OMLB01

In the tests of G4OMLB03 and G6OMLB01, the displacement and V_s were monitored simultaneously. The relationships between V_s and time are shown in Fig. 4 and 5 for G4OMLB03 and G6OMLB01, respectively, at each loading stage. It was observed that the shear wave velocity increases with time. When the curves of normalized displacement ($D(t)/D(t=0)$) vs. $\log t$ and normalized shear wave velocity ($V_s(t)/V_s(t{=}0)$) vs. $\log t$ at the loading stage 600kPa of test G6OMLB01 are plotted together as shown in Fig.6, it is obvious to notice a striking similarity of pattern between them. It demonstrates that the increase in V_s during primary consolidation is attributed to the development of the effective stress and the decrease in void ratio.

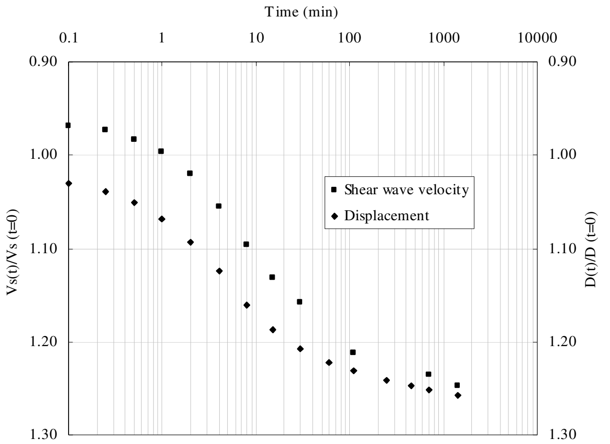

Figure 6 Normalized displacement and normalized shear wave velocity vs. time at the loading stage σ_v'=600kPa for the test G6OMLB01

With the results of the displacement vs. $\log t$, the value of coefficient of consolidation (c_v) can be determined, then the time factor T_v and the average degree of consolidation, U at each measurement point can also be obtained. Fig.7 shows the variation of shear wave velocity with the average degree of consolidation. It is observed that V_s drops slightly immediately after loading (this is also manifested in Fig.6, as the value of $V_s(t)/V_s(t{=}0)$ at the beginning of the test is smaller than 1), after which V_s increases approximately linearly with increasing average degree of consolidation up to U =100%. After the completion of primary consolidation V_s continues to increase due to aging effect of clay. The increasing amplitudes of V_s in the primary consolidation process are not the same for different loading stage and are dependent on the magnitude of the stress increment. The initial dropping of V_s may be caused by the breakdown of soil structure just after loading (Nakagawa et al. 1995).

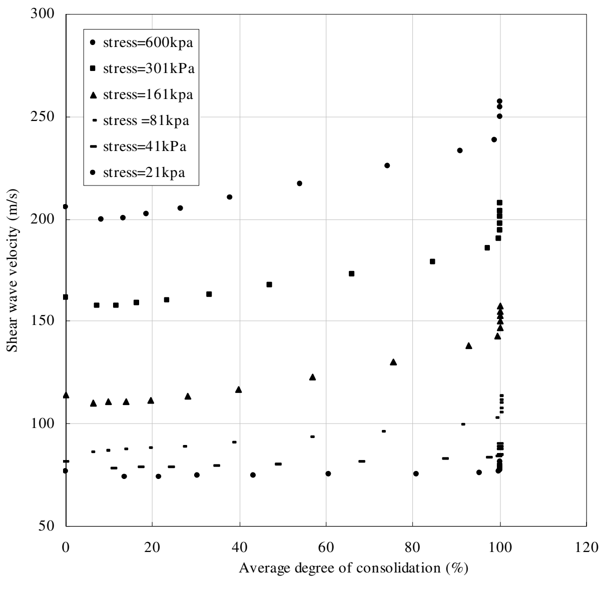

Figure 7 Shear wave velocity vs. average degree of consolidation at each loading stage for the test G6OMLB01

Also, the value of V_s after 24-hours at each load increment is plotted against the loading stress in log-scale in Fig.8. It is observed that there is almost linear relationship between log V_s and $\log \sigma_v'$ except at the initial stage where OC condition was expected. Since Macau marine clay is a newly deposited material and usually exhibits normally consolidated behavior, the values of shear wave velocity in NC stage are selected for the following analysis.

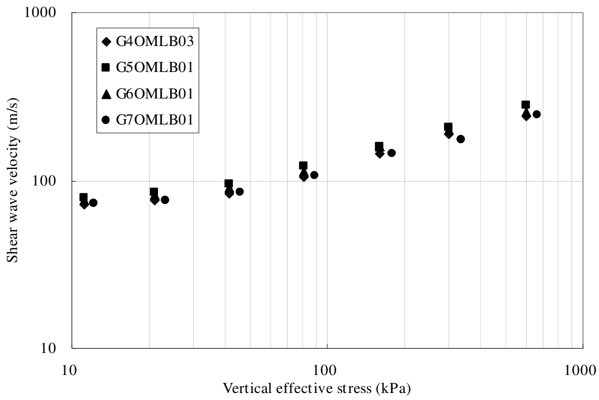

Figure 8 V_s vs. vertical effective stress for reconstituted samples

The variation of V_s in NC stage with applying stress σ_v' and void ratio e are shown in Fig.9 and Fig.10, respectively. It demonstrates that the value of V_s increases with the increase of effective stress and decrease of void ratio. Empirical Equations 1 and 2 can be used to correlate V_s to σ_v' and e, respectively.

$$V_s = 17.742(\sigma'_v)^{0.4182} \tag{1}$$

$$V_s = 2218.9\exp(-2.0326e) \tag{2}$$

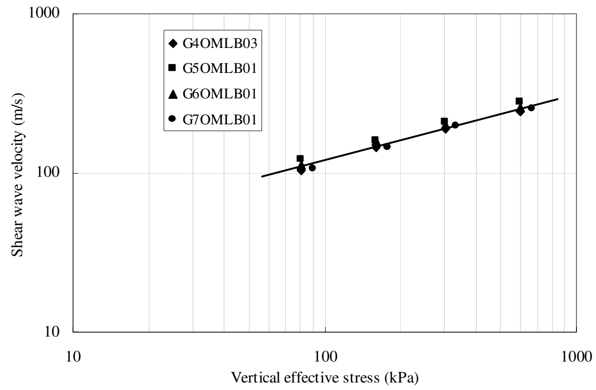

Figure 9 V_s/ vs. loading stress for reconstituted samples

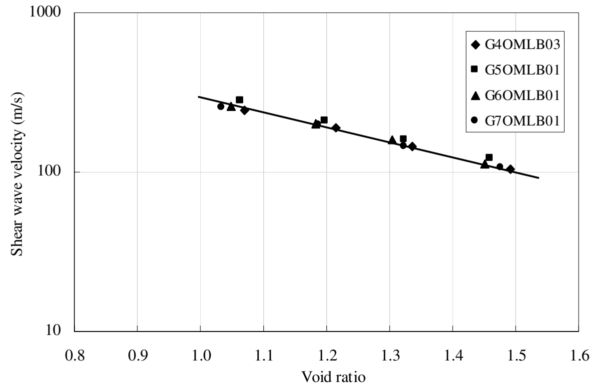

Figure 10 Shear wave velocity vs. void ratio for reconstituted sample

The coefficients of correlations for Equations 1 and 2 are $R^2 = 0.9636$ and 0.9795, respectively.

In normally consolidated stage, change of void ratio is related to the loading stress as described by the virgin compression line:

$$e = e_1 - \lambda \ln(\sigma_v') \quad (3)$$

where:
λ = slope of virgin compression line
e_1 = void ratio at $\sigma_v' = 1$ kPa

Based on the test results summarized in Fig.11, the relationship between void ratio and loading stress can be described by Equation 4 with coefficient of correlation, $R^2 = 0.991$.

$$e = 2.3798 - 0.2065 \ln \sigma'_v \quad (4a)$$

or

$$\sigma'_v = 101160 \exp(4.8426e) \quad (4b)$$

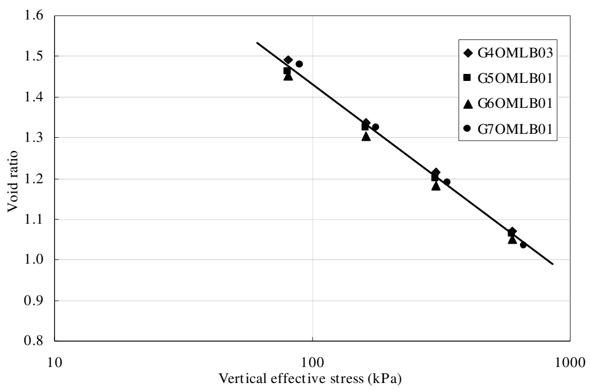

Figure 11 void ratio vs. effective vertical stress

After substituting Equation 4 into Equation 1, the following equation can be obtained:

$$V_s = 2198.3 \exp(-2.025e) \quad (5)$$

Equation 5 is very similar to Equation 2. Since e and σ_v' are uniquely related in the NC stage by the virgin compression line, the value of V_s can be expressed as a function of either one of these two parameters, σ_v' or e.

5 SUMMARY AND CONCLUSIONS

In this study, totally four consolidation tests on reconstituted specimens of Macau marine clay were performed simultaneously with shear wave velocity measurement.

It was observed that the value of shear wave velocity drops slightly immediately upon loading, after which V_s increases approximately linearly with increasing average degree of consolidation from U≈10% up to U=100%. After the completion of primary consolidation, V_s continues to increase due to aging effect of clay.

Also, two different equations are proposed to correlate the value of shear wave velocity to the loading stress and the void ratio after the primary consolidation. Since e and σ_v' are uniquely described by the virgin compression line in the NC stage, the value of V_s can be expressed as a function of either one of these two parameters.

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