Effect of Consolidation Time on Dynamic Shear Modulus of Soft Clay

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ABSTRACT :

The hardened effect that represents the soft clay harden gradually with the increment of consolidation time, makes dynamic shear modulus of soft clay increased; meanwhile, the size effect that represents the height and diameter of the sample decreased gradually, also produces effects on dynamic shear modulus of soft clay. A serial of free vibration column tests of soft clay was conducted to analyze the effects of consolidation time on maximal dynamic shear modulus, dynamic shear modulus ratio and sample's size of soft clay. According to the basic principle of the free vibration column test, the effects of varied size of sample on dynamic shear modulus of soft clay are analyzed. Combined with the relationships between consolidation time and sample's size obtained from the tests, the size effects of consolidation time on maximum dynamic shear modulus of soft clay are analyzed.

KEYWORDS: consolidation time, sample size, soft clay, dynamic shear modulus, free vibration column test

1. INTRODUCTION

Soft clay widely exists in the Yangtze River Delta region and the Zhujiang River Delta region in China. It always has some physics and mechanical properties adverse to engineering safety, such as high moisture content, large void ratio, high compressibility, and etc. Those issues call geotechnical engineering workers extensively attention. Meng Qingshan et al(2004) studied dynamic response characteristics and reinforcement effect of muddy soft clay applied impact loading using dynamic consolidation laboratory tests. Qi Jianfeng et al (2008) discussed the effects of graded loading and cyclic stress coupling on dynamic properties such as shear modulus at large strain using cyclical shear tests and vertical-torsion coupling tests. Those tests were on unconsolidated and undrained condition and they did not study the effect of consolidation time on dynamic shear modulus of soft clay. The effect of consolidation time on dynamic shear modulus of soft clay in laboratory tests should include following two parts: one part is the variety of dynamic shear modulus due to the samples hardened with increment of consolidation time (hardened effect for short); another part is the variety of dynamic shear modulus due to the sample's dimension decrease with increment of consolidation time (size effect for short).

For the aspect of hardened effect, Afifi(1970), Drnevich(1967), Anderson and Stokoe(1978) made comprehensive and deeply researches. For example, Anderson and Stokoe(1978) used an increment coefficient of dynamic shear modulus to describe the dynamic shear modulus increased with consolidation time increasing, and put forward a method to predict site maximum dynamic shear modulus by the increment coefficient and the site consolidation time factor . But it did discuss the effect of consolidation time on the dynamic properties of soft clay which is more sensitive to consolidation time. In China, there is scarce relevant research report can be founded. Further, the dynamic shear modulus of soils which was measured by free vibration column test, cyclic triaxial test or other laboratory tests did not make correction according to consolidation time of the real site in site earthquake response analysis. It may brings inaccuracy results.

At present, the dynamic properties of soil are mainly obtained using free-vibration column (resonant column) test or cyclic triaxial test. Brennan et al(2005) made an attempt to measure dynamic shear modulus of soil using centrifuge test, but it was on basic research stage. Free-vibration column test using the wave propagation principles in a cylindrical soil sample to measure dynamic shear modulus has a high accuracy results, but meanwhile, it is affected by lots of factors, such as the ends effect between soil sample and pedestal (Drnevich V P, 1978), environmental noises (Kim D S, 1991), membrane effects (Drnevich V P,1985), coil magnetic field effect (Meng J, 2003) and so on. For the soft clay, besides above mentioned factors, the size effect also should be considered. With the increment of drainage consolidation time, the height and diameter of soft clay sample make decrease gradually. According to the principle of free vibration column test, the variety of sample's size inevitably affect on dynamic shear modulus greatly. For example, Anderson and Stokoe(1978)studied the relationship between consolidation time and the height of sample by test, but he did not consider the size effect on dynamic shear modulus. Sun Jing et al(2007) analyzed the effects of the error of sample's size on dynamic shear modulus adopting the concept of experimental error, and concluded that the relative error of sample's height has relatively large effect on dynamic shear modulus. However, the size effect on dynamic shear modulus of soft clay is a deterministic issue, if we use error analysis method, it does not reflect the deterministic effect of variety of sample size on dynamic shear modulus. So a deterministic method is necessary to analyze the size effect on dynamic shear modulus.

2. FREE VIBRATION COLUMN TEST OF SOFT CLAY

2.1 Testing Apparatus

Model GZZ-1 Resonant Column (free-vibration) test system, which was developed by Institute of Civil Engineering, Nanjing University of Technology, was employed. This apparatus could produce magnetic force by controlling the coil current. This magnetic force made cylindrical sample produce a certain amount of distortional displacement, and immediately, let the cylindrical sample free torsion vibration. At the same time, the data of the torsion vibration attenuation curve could gather automatically from the accelerometer installed on the additional mass. This apparatus has high accuracy and stable performance. The detail description of the apparatus could be consulted the documentation (Chen Guoxing, 2003).

2.2 Tested Samples

Soft clay samples were remolded. The clay had liquid limit moisture content w_L =42.3%, plastic limit moisture content w_p = 20.7% and plasticity index I_p =21.6. All soft clay had about 35% moisture content by added a certain amount of water and mixed fully. Soft clay was filled multiple into the saturator, and when overflowed, flatted both ends of saturator. And then a sample of 3.91cm in diameter and 8.0cm in height was prepared. During the filling process, special attention should be paid to minimize the air taken into the sample as care as possible. A little contrast of initial weight could not be avoided due to the above process of preparing samples. However, initial weights were controlled to be 170±2g, namely density to be 1.77±0.02g/cm^3.

2.3 Test Procedure and Test Program

The confining pressure applied to all samples was 150kPa, additional mass at the sample's top had 857.5g, namely the axial pressure applied to samples was 157kPa, that was, consolidation ratio Kc=1.05. During consolidation, soft clay sample was supported by two semi-cylindrical molds. Samples were consolidated on one-side drainage condition. When preset time reached, molds were removed; torsion displacement then applied on the sample; and the free torsion vibration attenuation curve was obtained at the same time. After those processes, the height and diameter of sample were measured. To reduce measurement error, height in two directions was measured twice, and diameters were measured at upper, middle and lower position of sample in two direction. For each sample dynamic shear modulus and size were measured at two consolidation time.

The testing parameter was the consolidation time. And the measured parameters were as follows: height and diameter of test sample; dynamic shear modulus. According to testing parameter and measured parameters, the test program was made as shows in Table.2.1.

Table.2.1 Test program

Sample number	Confining pressure (kPa)	Consolidation ratio K_c	Consolidation time（h）						
			6	12	18	24	30	36	42
GD1	150	1.05	√	√					
GD2	150	1.05		√	√				
GD3	150	1.05			√	√			
GD4	150	1.05				√	√		
GD5	150	1.05					√	√	
GD6	150	1.05						√	√

Note: the symbol '√'means at the corresponding consolidation time to measure the dynamic shear modulus and sample's size.

3. TEST RESULTS AND ANALYSIS

According to test's program, the dynamic shear modulus of sample GD1 was measured when consolidation time reaches 6h. During the process of practicable manipulation, when removing the semi-cylindrical molds, the sample collapse occurred. Similar phenomenon still occurs when another sample used. So, result of the sample GD1 did not obtained.

The upper part of sample still appeared an obvious swelling phenomenon when consolidation time was 12h as shows in Fig.1. With the increment of consolidation time, this swelling phenomenon reduces gradually and mostly vanished when consolidation time reached 36h. this made some effect on measuring diameter of sample.

The diameter data of sample measured at middle position were uniformly used in following analysis.

Fig.1 The swelling phenomenon of the sample

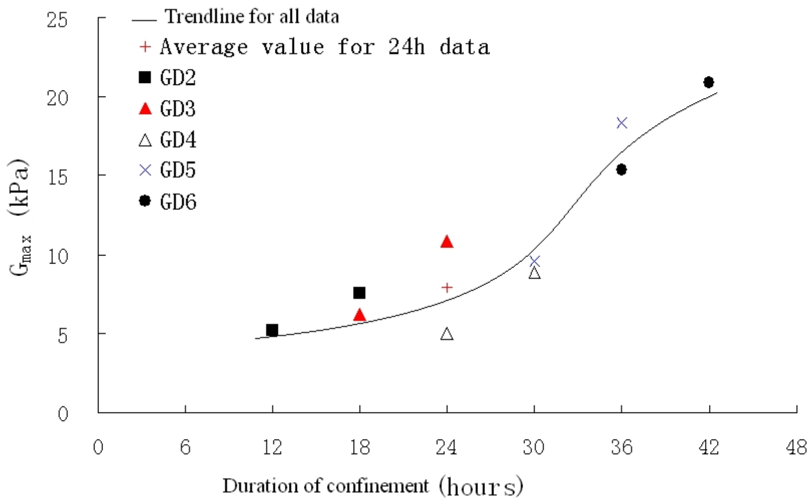

Fig.2 The relationship between consolidation time and maximum dynamic shear modulus

3.1 Effect of consolidation time on maximum dynamic shear modulus

Base on the relationship between dynamic shear modulus and shear strain by free-vibration column tests, the maximum dynamic shear modulus at variety of consolidation times *T* were obtained using the hyperbolic skeleton curve constitutive model. Fig.2 shows the relationship between maximum dynamic shear modulus of soft clay and consolidation time . It can be observed that: the two maximum dynamic shear modulus of the same sample increases with increasing of *T*; on the whole, the increasing tendency curve for all test results appears "S" form. At the stage of $T \leqq 30$h and $T \geqq 36$h, maximum dynamic shear modulus increases slowly; and at *T*=30～36h, maximum dynamic shear modulus increases quickly. This phenomenon may be related to the soft clay samples on one-side drainage condition. During the testing process, swelling phenomena of samples were observed at $T \leqq 30$h as mentioned above. It means that the upper part of samples was relatively softer, and the free vibration of soft clay sample was mainly subjected to the effect of softer part of sample at this time stage. At *T* =30～36h, the upper part of sample drains obviously, and the maximum dynamic shear modulus increases quickly. At $T \geqq 36$h, the whole sample finishes primarily drainage condition, and the maximum dynamic shear modulus of sample enters a slowly increasing stage.

Fig.3 compares the maximum dynamic shear modulus of soft clay samples in this tests with that of kaolin clay studied by Anderson and Stokoe[5] with variety of consolidation time *T*. Based on the tests of kaolin clay, Anderson and Stokoe[5] divided the hardened effect on dynamic shear modulus into two stage: primary consolidation stage and long-term consolidation stage. At the primary consolidation stage, kaolin clay's maximum dynamic shear modulus appears quick increasing. At the long-term consolidation stage, cementation slowly takes place among the particles of soil and the maximum dynamic shear modulus values increases slowly. Between the two stages, there is an inflection point, as shows broken lines in Fig.3. However, the maximum dynamic shear modulus values gotten in this test are obvious lower than kaolin clay's values. At the consolidation time *T* =720～2520min, kaolin clay has been in the long-term consolidation stage and the maximum dynamic shear modulus increased slowly, but for soft clay, it appears quickly increasing.

3.2 Effect of consolidation time on dynamic shear modulus ratio

Fig.4 shows the variation of relationships between dynamic shear modulus ratio and dynamic shear strain amplitude with variety of consolidation time *T*. It can be observed that dynamic shear modulus ratio decreases with shear strain, and obviously increases with the *T* extending. Fig.4 also gives the typical effected ranges suggested by Anderson et al[5] in small-time effect and large-time effect, as shows the ranges enveloped by broken lines in Fig.4. At *T*=12～18h, many data of dynamic shear modulus ratio are located at the high-boundary of the short-time effected range, and at T =30～42h, the dynamic shear modulus ratio of soft clay are almost located in the large-time effected range.

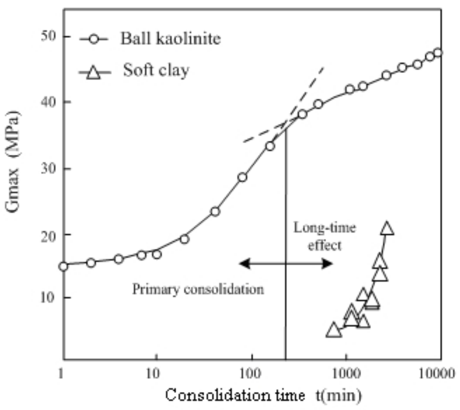

Fig.3 Comparison of maximum shear modulus increase for soft clay and kaolin clay

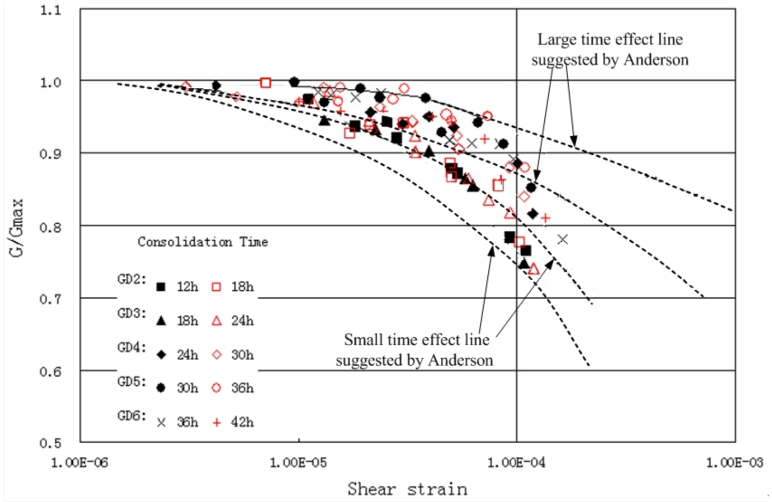

Fig.4 Variation of versus with consolidation time

3.3 Relationships between consolidation time and sample size

Fig.5 and Fig.6 show the relationships between consolidation time T and the height, diameter of samples measured from the tests. In average, the data of height decline with T extending, and also the data of sample's diameter. Anderson and Stokoe[5] also obtained that the height of sample decrease with T extending.

For soft clay, the functions and of sample's height and diameter versus consolidation time must be monotone decreasing functions. In order to simplified analysis, the relationships between T and size of soft clay sample employed a linear relation:

$$H = g_H(T) = a_H T + c_H \tag{3.1}$$
$$D = g_D(T) = a_D T + c_D \tag{3.2}$$

In above equations, T is consolidation time, the unit is hour; fitting parameters a_H =-0.0906, a_D =-0.0395; c_H , c_D are initial height and diameter of sample, here, they are 80.0mm and 39.1mm separately. At T =24h, the decreasing of sample's height and diameter are 2.7% and 2.4% separately.

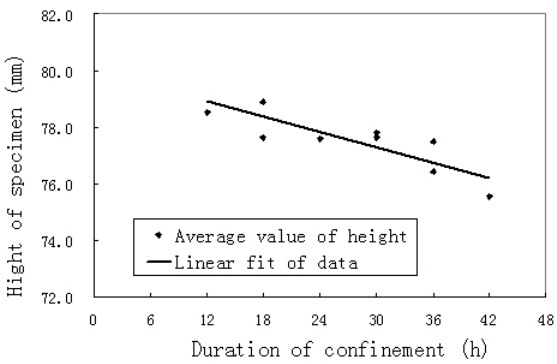

Fig.5 Relationship between height and consolidation time

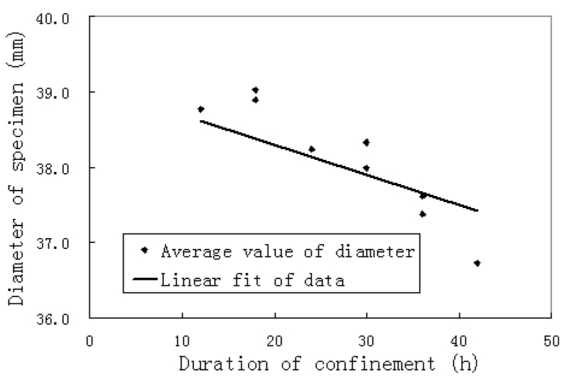

Fig.6 Relationship between diameter and consolidation time

4. THE SIZE EFFECT OF CONSOLIDTION TIME ON DYNAMIC SHEAR MODULUS

Based on the principle of free vibration column test(Chen Guoxing, 2007), the formula of dynamic shear modulus can be obtained, as follows:

$$G = \rho\left(\frac{2\pi f_n H}{\beta}\right)^2 \tag{4.1}$$

In which: ρ is the density of sample; f_n is the free vibration frequency of sample; H is the height of sample, and β can be obtained by Eqn.4.2.

$$\beta \cdot tg\beta = \frac{I}{I_0} \tag{4.2}$$

In which: I_0 is the polar moment of inertia of additional mass, here, I_0=24.529*kg·cm*^{2}; I is the sample's polar moment of inertia. Natural unit weight of soils is usually within 13~20*kN/m*^{3}, so the range of $\frac{I}{I_0}$ is in 0.010~0.016. Using a linear equation Eqn.4.3 to fit Eqn.4.2, the relationship of β and $\frac{I}{I_0}$ can be obtained.

$$\beta = \mathrm{A}\frac{I}{I_0} + \mathrm{B} = \mathrm{A}\frac{\rho\pi \mathrm{D}^4 H}{32 I_0} + \mathrm{B} \tag{4.3}$$

In above equation, *D* is the diameter of sample; *A, B* are fitting parameters; and for model GZZ-1 free vibration column test system, *A*=4.3775; *B*=0.0566, correlation coefficient R^2= 0.9991, which can satisfy the requirement.

The simplified explicit formula between dynamic shear modulus and the height, diameter of sample can be obtained by substituting Eqn.4.3 into Eqn4.1, as follows:

$$G = \rho\left(\frac{2\pi I_0 f_n H}{AI + BI_0}\right)^2 = \rho\left(\frac{64\pi I_0 f_n H}{A\rho\pi D^4 H + 32 B I_0}\right)^2 \tag{4.4}$$

The effect of individual changing by height and diameter of sample on the increment of dynamic shear modulus is given in Fig.7. It can be observed that: The dynamic shear modulus of sample can increase with the reduction of diameter and decrease with the decrease of height; and the effect degree from decrease of height equal to twice the one from reduction of diameter. Sun Jing and Yuan Xiaoming got the similar results by studying the relationship between the relative error of dynamic shear modulus and that of sample's size.

By substituting Eqn.3.1 and Eqn.3.2 into Eqn.4.4, a determined relationship between dynamic shear modulus and consolidation time can be given as follow:

$$G = \rho\left(\frac{64\pi I_0 f_n g_H(T)}{A\pi\rho g_D^4(T) g_H(T) + 32 B I_0}\right) \tag{4.5}$$

In order to eliminate the hardened effect of consolidation time on dynamic shear modulus, the increasing percentage factor F_D can be described the size effect of consolidation time on dynamic shear modulus.

$$F_D = \frac{\Delta G}{G_T} \times 100\% \tag{4.6}$$

In which ΔG is the variable quantity of dynamic shear modulus due to varied consolidation time by size effect; G_T is the dynamic shear modulus at the consolidation time T measured by free-vibration column test.

Using the linear relationships of consolidation time and sample size measured in this test, relationship between the increasing percentage factor F_D and consolidation time T can be obtained as shows in Fig8. The F_D decreases obviously with the increasing of consolidation time in the range of T≦42h. If the consolidation time T =24h, dynamic shear modulus decreases 3.2% due to the decreasing of soft clay sample's size.

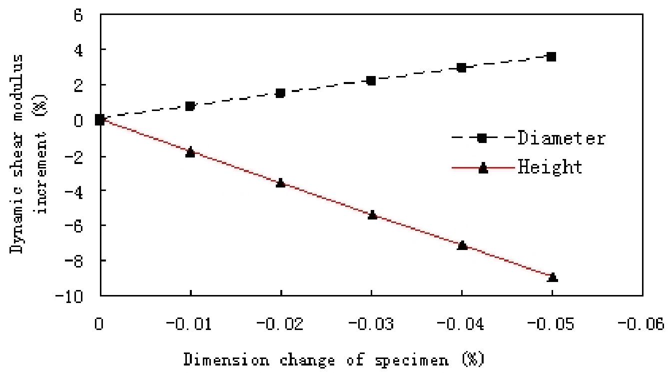

Fig.7 The size effect of sample

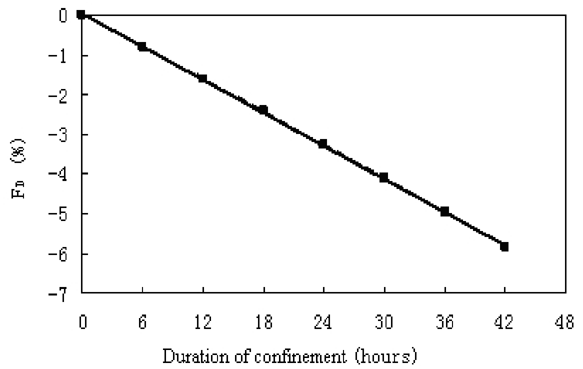

Fig.8 Relationship between dynamic shear modulus and consolidation time due to varied sample size

5. CONCLUSIONS AND SUGGESTIONS

Through analyzing the results of dynamic shear modulus on soft clay and the principle of free vibration column test, the following conclusions can be obtained.

1. In the hardening effect aspect of soft clay, maximum dynamic shear modulus and dynamic shear modulus ratio are affected significantly by consolidation time.

2. Sample's height and diameter obviously decreases with the increasing of consolidation time. So if the effect of size effect on dynamic shear modulus is neglected, it will have obvious effect on the validity of test's results. Dynamic shear modulus of specimen measured by this test increase gradually with the increasing of consolidation time.

It is deterministic issue about the size effect of dynamic shear modulus on soft clay from consolidation time. Based on sufficient amount of consolidation tests, the functional relationships between the height, diameter of sample and consolidation time can be obtained. Then using Eqn.4.5 and Egn.4.6, the relationship between consolidation time and dynamic shear modulus can be built. At last, a modified dynamic shear modulus considered the size effect can be obtained by multiplying the increasing percentage factor F_D to the dynamic shear modulus measured by free-vibration column test.

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