Experimental Research on the Dynamic Shear Modulus and Damping Ratio of Marine Structured Clay

Meng Zang¹, Lu Li¹ and Weiwei Wang¹

¹School of Civil Engineering and Architecture, Wuhan Polytechnic University, Wuhan 430023, China

Abstract. The dynamic shear modulus and damping ratio are essential parameters for the dynamic properties of clay. They play significant role in dynamic analysis of soil mass as well as the safety evaluation on site earthquake. In consideration of the specialty of marine structured clay, the resonant column test was used to analyze the Zhanjiang structured clay. From the result, currently the standard recommended values of shear modulus and damping ratio are not applicable to the marine clay. Therefore, it used the Martin-Davidenko model along with the empirical relationship of damping ratio and shear strain to build the regularity of the shear modulus and damping ratio versus the changes of shear strain. Consequently it proposed the recommended value of the shear modulus $G/G_{\text{max}}$ and the damping ratio $D$ for the marine structured clay within the strain range of $5 \times 10^{-6}$ ~ $5 \times 10^{-3}$. The research findings can provide technical foundation for the engineering design, construction and anti-seismic analysis of Zhanjiang structured clay.

1. Introduction

With the spread of our national engineering construction scope as well as the increasing quantity and scale of marine engineering, when it comes to the seismic safety evaluation and the analysis on dynamic response of foundation at such engineering sites, reasonable values of marine clay shear modulus $G$ and damping ratio $D$ will have direct impact on the safety and economy of the engineering. Normally the rigidity, strength and deformation of marine clay are related to structural characteristics[1-2]. Taking into account of the regional characteristics and the particularity of marine clay, among existing specifications and recommended values[3-4], the empirical values of kinetic characteristic parameters for normal clay are not universal to the marine structured clay. Thereupon it is so imperative to figure out certain typical kinetic parameters for the marine structured clay, thus providing technical basis for the design, construction and anti-seismic analysis of marine engineering sites. Accordingly, it has great significance for the experimental study on the interior dynamics of marine structured clay in engineering construction. The resonant column is regarded as the most reliable method in laboratory test to measure the small-strain shear modulus of soil[5]. In accordance with the shear modulus $G$ and damping ratio $D$ corresponding to various shear strain value $\gamma$, the attenuated curve that describes the small-strain rigidity versus strains was obtained.

On the basis of above research status, this paper used the resonant column test method to probe into the changing regularity of the shear modulus and damping ratio as per the changes of shear strain on marine structured clay. It studied the rationality of dynamic decay properties on marine structured clay by analyzing the corresponding theoretical model and empirical relationship. In addition, by comparative analysis on the recommended values and the diversity of dynamic characteristic parameters in marine clay, which were advocated by the scholars at home and abroad in addition to the
specifications, it proposed the appropriate recommended values of shear modulus $G/G_{\text{max}}$ and damping ratio $D$ within certain scope of strain for Zhanjiang marine structured clay.

2. Soil Specimen and Experimental Method

2.1. Soil Specimen
The experimental specimen stems from the depth of 15.0~20.0m in Xiashan District, Zhanjiang City, Guangdong Province. Its physical and mechanical indexes of Zhanjiang structured clay were shown in Table 1. This soil possesses high moisture content and large void ratio in terms of physical characteristics. Furthermore, its clay particle content exceeds 50% and the permeation coefficient in vertical direction is rather small. Therefore, this sample possesses inferior physical properties but superior mechanics properties. The high-quality undisturbed sample was drilled by means of thin wall sampler with fixed piston. And the remolded soil was processed by rubbing method so as to completely destruct the original structure. Then the muddy soil specimen was remolded.

2.2. Experimental Method
The resonant column system (GDS RCA) was used in the resonant column test on the undisturbed clay and the remolded clay respectively. First, graded consolidation test (isotropic consolidation) was implemented on the specimen. Under primary-grade pressure, the consolidation settlement and displacement of specimen were tested after drainage consolidation. Then increased by grades, the vibration stress was added on the specimen to scale the resonance frequency and relevant shear strain in its reverse direction. Again, it tested the vibration attenuation curve of the soil mass after switching off the power; and it calculated the volume change and void ratio of the specimen. In accordance with Formula (1), the dynamic shear modulus of the test sample was computed. And then it proceeded with next grade of consolidation until all grades of consolidations were completed. The specimen possessed 50mm in diameter and 100mm in height. To fulfill 98% saturation for test, two steps of saturating treatment were done: pumping vacuum saturation and back-pressure saturation. The effective confining pressure of undisturbed clay at each grade was respectively: 50kPa, 100kPa, 200kPa, 300kPa, 400kPa, 500kPa, 600kPa, 700kPa, 800kPa and 900kPa.

The shear modulus $G$ could be calculated by the resonance frequency, the density and the geometrical dimensions of specimen as follows:

$$G = \rho v_s^2 = \rho \left( \frac{2\pi f H}{\beta} \right)^2$$  \hspace{1cm} (1)

In the formula, $G$ represented the dynamic shear modulus of clay specimen; $\rho$ represented its mass density; $f$ represented the torsion vibration resonance frequency; $H$ represented the height of clay specimen; $\beta$ represented the characteristic value of the torsion vibration frequency equation.

The damping ratio was computed in accordance with the logarithmic decrement of free-vibration attenuation curve as follows:

$$D = \sqrt{\frac{\delta^2}{4\pi^2 + \delta^2}}$$  \hspace{1cm} (2)
3. Experimental Result of Resonant Column Test

Under different consolidation pressures, the correlation curve of the dynamic shear modulus G and the shear strain γ in Zhanjiang structured clay was shown in Figure 1. G decreased gradually as γ grew. When γ was relatively smaller, G decreased at a relatively slower rate. In case the shear strain increased by certain degree, the shear modulus started to reduce rapidly. The initial excitation voltages were all set as 0.005V. By comparison of the test curves of undisturbed clay and remolded clay, under the same excitation voltage, when the consolidation pressure grew up, the tested minimum shear strain diminished. Furthermore, its shear modulus decreased at more prominent rate in case the shear strain enlarged.

![Figure 1](image1.png)

(a) Undisturbed clay  
(b) Remolded clay  

Figure 1. Relationship between shear modulus G and shear strain γ of Zhanjiang clay

Figure 2 indicated the changing curve of the damping ratio D versus the changes of shear strain γ in both undisturbed clay and remolded clay under different confining pressures. As shown in Figure 2(a), the damping ratio of undisturbed clay specimen all increased with the growth of shear strain. Not only that, to a certain extent when the shear strain grew up, its damping ratio would sharply enlarge. In comparison with Figure 1(a), the rapidly diminishing phase of shear modulus is correspondent to the sharply growing phase of damping ratio. However, the growth curve of damping ratio D versus the growth of shear strain γ for remolded clay presented a relatively smoother trend.

![Figure 2](image2.png)

(a) Undisturbed clay  
(b) Remolded clay  

Figure 2. Relationship between damping ratio D and shear strain γ of Zhanjiang clay

3.1. Relation Curves of Marine Clay $G/G_{max}$ and $D-\gamma$

In accordance with the relation of dynamic shear modulus and damping ratio against the shear strain under different consolidation pressures in Figure 1(a) and 2(a), Gmax normalization processing was done on the shear modulus G of undisturbed clay under different consolidation pressures, which was shown in Figure 3(a). In the Figure, the maximum shear modulus Gmax of undisturbed clay and remolded clay under different consolidation pressures were available in references[6]. The relation curve
of G/Gmax-γ and D for normal clay as well as relevant research findings and specifications by Zhu[7], Vecetic[8], Chen[9], Yuan[3] and Standard value[4] were also added in Figure 3. Comparative analysis was undertaken to study the difference between structured clay and other clays. As was shown in Figure 3, under different consolidation pressures, the distribution zone of test sites for Zhanjiang structured clay was relatively narrower. It resembled the researching results by Zhu. The determination of G/Gmax value was basically independent of the strain status for soil mass. Moreover, indicated by the studying results of structured clay by Zhu, Vecetic, Yuan, Chen and this paper, the testing sites of marine clay were almost identical. All of them were distributed above the standard value. That was, the testing sites were apparently above the standard value. So if the dynamic parameters were selected as per previous standard value, it was too conservative. Thereupon, it was suggested not to select the recommended value of current standard as the G/Gmax value of Zhanjiang structured clay. In case the strain value was less than 10-4, the damping ratio of Zhanjiang clay was mainly in the vicinity of the researching values by Chen and Yuan; when the strain value was more than 10-4, the testing sites started to disperse. The value D of Zhanjiang clay was lower than the standard value and most other researching results. Otherwise, the result of damping ratio D was a bit larger than G/Gmax. It complied with people’s cognition of damping as of now.

3.2. Description Method of Shear Modulus G and Damping Ratio D
Zhanjiang clay is a kind of high-structured and high-strength sensitive clay. So the designed parameter is not suggested to follow the previous research findings or standard values of cohesive soil. It is supposed to evaluate the dynamical behavior of the marine structured clay in light of its actually measured parameter values, and to further propose appropriate recommended values of the kinetic parameters for the marine structured clay. Through comparative analysis, the Martin-Davidenko model[10] was selected to implement fitting analysis on the experimental data of the dynamic shear modulus ratio curve for Zhanjiang marine clay as below:

\[
G(\gamma) = G_{\text{max}} (1 - f(\gamma))
\]

\[
f(\gamma) = \left( \frac{\gamma/\gamma_0}{1+(\gamma/\gamma_0)^{2B}} \right)^A
\]

In this model, \(\gamma_0\), A, B were all fitting parameters which possessed soil properties. The relationship between the damping ratio and the strain was expressed as below:

\[
D = D_{\text{min}} + D_{\text{max}} (1 - \frac{G}{G_{\text{max}}})^n
\]

In this formula, \(D_{\text{min}}\) referred to the minimum damping ratio. It was the basis damping ratio of soil mass, which was relevant with the property, the consolidation status and else factors of the clay; \(D_{\text{max}}\)
referred to the maximum damping ratio. In case of G=0, then D=Dmax. And n referred to the fitting parameters which were related with the clay property.

For Zhanjiang marine structured clay, the dispersion of test sites for undisturbed clay and remolded clay at different strain levels were relatively smaller. Their distribution zones were relatively narrower. The distribution of testing sites for undisturbed clay and remolded clay under different consolidated confining pressures as well as the fitting curve of model were shown in Figure 4. The analysis showed that, Martin-Davidenkov model and the selected empirical formula of damping ratio changes corresponding to the strain changes could perfectly fit the developing and changing regularity of G/Gmax and D for Zhanjiang clay

![Figure 4. Relationship curves of G/Gmax-γ and D-γ for Zhanjiang clay](image)

Table 2 Fitting parameters of undisturbed clay and remolded clay

| Samples          | A     | B     | γ0    | Dmax  | Dmin  | n     |
|------------------|-------|-------|-------|-------|-------|-------|
| Undisturbed clay | 0.4829| 0.8572| 0.2452| 14.1179| 1.7737| 1.4529|
| Remolded clay    | 0.2716| 1.5115| 0.3078| 9.4038 | 0.2644| 0.3637|

Table 3 Recommended parameters of G/Gmax-γ curve and D-γ curve for Zhanjiang clay

| Samples          | Recommended parameters | Shear strain γ/10^{-2} |
|------------------|------------------------|------------------------|
|                  |                        | 5×10^{-4}  | 1×10^{-3}  | 5×10^{-3}  | 1×10^{-2}  | 5×10^{-2}  | 1×10^{-1}  | 5×10^{-1}  |
| Undisturbed clay | G/Gmax                 | 0.9941      | 0.9895      | 0.9602      | 0.9294      | 0.7400      | 0.5668      | 0.1173      |
|                  | D/%                    | 1.7819      | 1.7926      | 1.9043      | 2.0737      | 3.7680      | 5.9606      | 13.5511     |
| Remolded clay    | G/Gmax                 | 0.9949      | 0.9909      | 0.9660      | 0.9400      | 0.7753      | 0.6062      | 0.0548      |
|                  | D/%                    | 1.6459      | 1.9636      | 3.0121      | 3.6440      | 5.7273      | 6.9644      | 9.4772      |

The fitting parameters of Zhanjiang structured clay by Martin-Davidenkov model and the selected empirical formula that expressed damping ratio corresponding to strain were shown in Table 2. After reorganization of the experimental results, the model fitting curve of G/Gmax changing as the changes of γ, along with the empirical relation of D and γ, it presented the recommended value of G/Gmax and D within the strain range of 5×10^{-6}~5×10^{-3}, which was shown in Table 3. It provided technical foundation for the engineering design and construction of Zhanjiang structured clay. It indicated that the recommended value G/Gmax of Zhanjiang clay decreased with the growth of γ; the recommended value D increased corresponding to the growth of γ. Both of the variation curves showed hyperbolic distribution, which favorably reflected the changing regularity of the kinetic parameters for Zhanjiang
marine clay. It was shown from the impact analysis on fitting parameters A, B and γ0 versus G/Gmax-γ curve. Fitting parameters A and B determined the shape and curvature of curve. Under the same condition, the value A increased to bring the complete G/Gmax-γ curve upward; the value B increased to make the G/Gmax-γ curve decay sharply. In Table3, when the strain range γ < 5×10^{-3}, the recommended value G/Gmax of undisturbed clay was slightly lower than that of remolded clay. However, when γ=5×10^{-3}, the recommended value of undisturbed clay was higher than that of remolded clay. In addition, the fitting parameter value B of remolded clay was larger than that of undisturbed clay. It also proved that the recommended value G/Gmax of remolded clay decayed more sharply as γ increased. The recommended value of damping ratio D for remolded clay was lower than that of undisturbed clay.

4. Conclusions

(1) Under the same excitation voltage, the consolidation pressure and the minimum testing shear strain presented a kind of decreasing function relationship. What was more, the dynamic shear modulus decreased at a more prominent rate as the shearing strain grew.

(2) The currently recommended values of specified shear modulus and damping ratio were not applicable to marine structured clay. By using the Martin-Davidenkov model together with the empirical relationship of damping ratio and shear strain, it set up the changing regularity of shear modulus and damping ratio against the changes of shear strain on Zhanjiang marine clay.

(3) It presented appropriate recommended values of shear modulus G/Gmax and damping ratio D for the marine structured clay within the strain scope of 5×10^{-6}~5×10^{-3}. The recommended value of Zhanjiang clay G/Gmax decreased with the increase of γ, the recommended value of damping ratio D increased as γ increased. Additionally, the dynamic characteristics parameters between marine structured clay and remolded clay were kind of different.

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