Study on Hollow Cylinder Torsional Shear of Dynamic Properties of Two Soils

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ABSTRACT

The testing is employed to perform cyclic torsional shear test on hollow cylinder sample under isotropic consolidated condition with static and dynamic universal triaxial and torsional shear soil testing apparatus. The authors conducted three dynamic torsional with single sample achieving dynamic properties under three confining pressures with saturated clay and undisturbed silty clay. Special attention was paid to the maximum dynamic shear modulus Gmax and ξ obtained from single sample of cyclic torsional shear test was basic approximated with traditional method of dynamic torsional test. Based on the test results and theoretical analysis, the confining pressure had a significant influence on the dynamic shear modulus and feeble influence on the dynamic damping ratio with the single sample method. It was also found that the G of two soils decreases when the confining pressure decreases from 400kPa to 100kPa and the decreasing gradient of G is less than the increasing gradient of G from 100kPa to 400kPa. The relation of G and ξ can be fitted by logarithm equations in this paper. Furthermore, this method can diminish the difference of the sample during experiment and effectively provide convenience with authentic experimental results.

KEYWORDS: dynamic torsional test; hollow cylinder sample; saturated clay; undisturbed silty clay, dynamic shear modulus; damping ratio

INTRODUCTION

As an important aspect on the research of the soil dynamics, the dynamic shear modulus and damping ratio are the two principal parameters by Seed (1970), which can be required to set up the model of Hardin-Drnevich (1972), to describe the stress-strain relationship. In order to investigation on the dynamic shear modulus and damping ratio of soil, free vibration method by resonant column apparatus were carried for different soils by Gu et al. (1995) and Yuan et al. (2000). It was shown by Xie et al. (1988) that on occasion of small strain; one sample could be loaded progressively, according to the test of measuring module and damping ratio. Through the dynamic triaxial test by Guo et al. (2006), it proved that to load multileveled on one sand sample could be practicable. After many years of experimental investigation, according to many types of soil sample, dynamic properties under triaxial test by He et al. (1997) use one specimen on 20 level loads after changing confining pressure or consolidation ratio and keeping on consolidation and

Recognized as the perfect test on research of soil dynamic property, the dynamic trosional test is the ideal method to measure dynamic property, according to which, the dynamic property of dynamic trosional tests on clay and silty clay were discussed in this paper. Guo *et al.* (2006), He *et al.* (1997) and WANG *et al.* (2005) have measured the module and damping ratio using one sand sample on the dynamic triaxial apparatus, and demonstrated the reliability of test results, without the discussion of feasibility to get dynamic shear modulus and damping ratio through the dynamic trosional test of progressive loading after changing confining pressure of single sample under the small strain. Therefore, it is discussed that the method of getting dynamic shear modulus and damping ratio curve of saturated clay and undisturbed silty clay through changing the confining pressure (including imposed and reduced pressure) by single sample, the result of which was compared with the result of the dynamic trosional test under three different consolidation pressures by three independent samples respectively.

TEST EQUIPMENT AND EXPERIMENTION PROCEDURE

Soil Sample Preparation

Due to the difficulty of obtaining of uniform saturated clay sample, the research on hollow cylinder torionsal shear of dynamic properties of clay have not been system investigated. The hollow cylindrical specimens used in this study were prepared by using the vacuum suction method first reported by Yan (1991). Considering the Poisson ratio at initial state of undisturbed silty clay approached to 0.44 and the problems of losing water of the specimens in transportation and preservation, the pore water pressure coefficient of each sample was assured to reach more than 0.98 by the saturation of applying backpressure de-aired water. The basic physical property indices of the samples are listed as Table 1.

Table 1: Physical property of the clay and silty clay samples

	ρ ($t\cdot m^{-3}$)	w %	G_s	w_p %	w_l %	I_p	S_r %
saturated clay	1.95	29	2.67	18.12	36.2	18	>98
silty clay	1.92	17	2.65	14.03	23.1	9.07	>98

For the hollow-cylinder clay samples used in the study, the outer- and inner-diameters of the sample are 70mm and 30mm respectively and the height is 100mm. Saturation of the sample is fulfilled by pouring de-air water and by exerting back pressure. The sinusoid cycle load was adopted in the cycle torsion shear test, with frequency of 0.1Hz and applying equal confining pressure both inside and outside at same time

Test apparatus

The soil static and dynamic universal triaxial and torsional shear apparatus provided by Dalian University of Technology and Seiken Inc. and made by Seiken Inc. allows the individual control of axial load, torque, frequency and phase difference in noninterference state to perform axial-and-torsional coupling shear test or cyclic torsional shear test. The apparatus consists of five components including main unit, air-water unit (air compressor and vacuum pump), simulation control unit, computer collecting unit and hydraulic loading unit (hydraulic actuators and hydraulic supply) The details are presented by Luan *et al*. (2003).

Test Procedure

Put one sample of saturated clay and another sample of undisturbed silty clay respectively into 100kPa consolidated pressure firstly, and then applies about 20 level different loading at frequency of 0.1Hz with 5 cycles per load level to the same samples, keep on the consolidation respectively at 200kPa and 400kPa consolidation pressure and apply cyclic loading sectional; to the same sample, reduced the consolidation pressure to 200kPa and 100kPa and then reconsolidate it by applying cycle loading sectional, measuring the *G* and *ξ* of soil when rebounding under degressive consolidation pressure relevantly. Compared with the result of dynamic torsional test about dynamic property by adopting three independent samples of two kinds of soil samples at 100, 200and 400kPa confining pressure, the former kind of curve went around the later one within 20%. It can make sure the reliability of experimental results and analyses to use the method of getting dynamic property of different consolidated pressures (including imposed and reduced pressure) with single sample.

ANALYSIS OF DYNAMIC SHEAR MODULUS RESULTS

The G∼γ relation curve of single sample with imposed pressure

Based on the curve of hysteric relationship of *τ* and *γ* in the condition of cyclic stress, the dynamic shear modulus of different strain levels can be gotten. In the condition of avoiding pore water pressure raise obviously, the changing law of *G* with *γ* of single sample due to two kinds of soil samples consolidated in different confining pressures, as Fig 1. *G* and G_{max} are both growing with the increase of confining pressure, the reason of which is that when applying confining pressure, the grains inside the sample come to a thickening trend continually, the void ratio decreases and the grain contact point of soil increases, which makes the dynamic strain less and the slope of skeletal curve increase. It is also shown in the picture that the *G* of undisturbed silty clay is larger than that of saturated clay and the *G* of silty clay increases more when confining pressure increases, that is, the shear modulus of silty clay is more sensitive than that of clay, which shows that the element of clay in grain composition affects the property on elastic distortion of clay and silty clay in Dalian, and the characteristic of nonlinear dynamics as well.

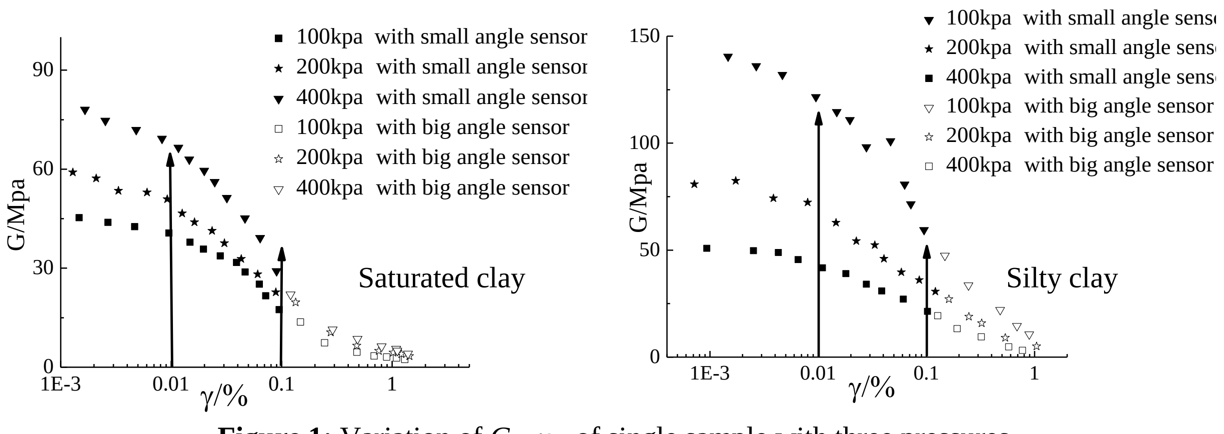

Figure 1: Variation of *G* ~*γ* of single sample with three pressures

The G∼γ relation curve of single sample with imposed and reduced pressure

According to each single sample of two kinds of soil, reduced the consolidation pressure to 200kPa and 100kPa, and then apply cyclic loading to get the reduced rebound *G*∼*γ* relation curve of the two soils in the degressive consolidation pressure as Fig.2. It is also shown in the picture that the dynamic shear modulus of two kinds of soil decreases after confining pressure reduced, but can be little larger than that of increase confining pressure. That is, the *G* decreases as the pressure reduced and the descending gradient is smaller than that of imposed gradient with increasing pressure.

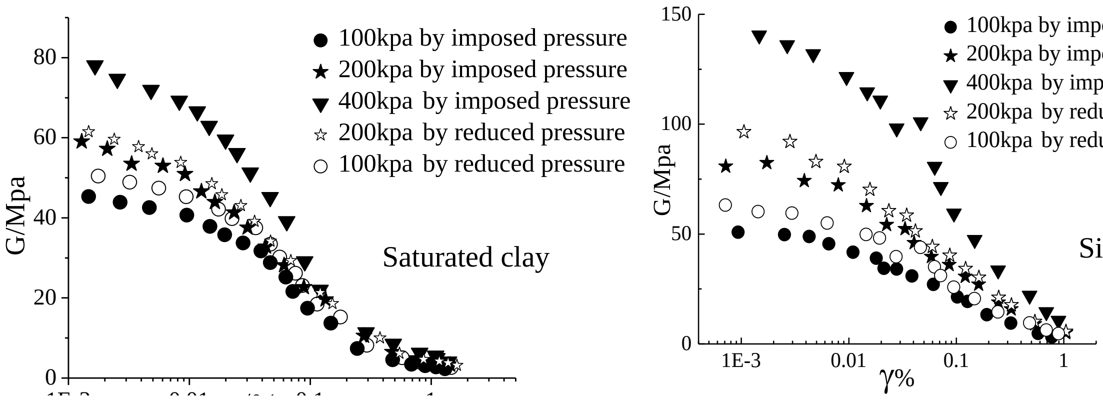

Figure 2: Variation of $G \sim \gamma$ by imposed and reduced pressure

The G～γ relation curve measured by two methods

The experimental result of measuring G by one sample of multiple consolidations can be compared with the one by three single sample, from which the $G \sim \gamma$ relation curve should be gotten as Fig.3. (In the picture, the solid icon stands for Method 1: the result of single sample by multiple consolidation; the hollow icon stands for Method 2: the result of three samples by respective consolidation.) As is analyzed from Fig.3, the trend change of the two $G \sim \gamma$ relation curve are affected a lot by the two methods, especially when $\gamma<10^{-3}$, that is, the influence in minute shearing strain amplitude value is very particular, but not when $\gamma>10^{-3}$ at all. The dynamic shear modulus of multiple consolidation by one sample is a little lower than the one of consolidation by three single samples, but when confining pressure comes to 400kPa, the difference between two curves enlarges, which shows that although the variant level increases as confining pressure increases, it can also ensure the reliability of experimental result basically, compared with the result of routine dynamic torsional test, especially in the confining pressure of 100kPa and 200kPa. As is also shown in Fig.3, the difference of undisturbed silty clay is larger than the one of clay when confining pressure is 400kPa, which probably relates to the internal structure of the two kinds of soil samples.

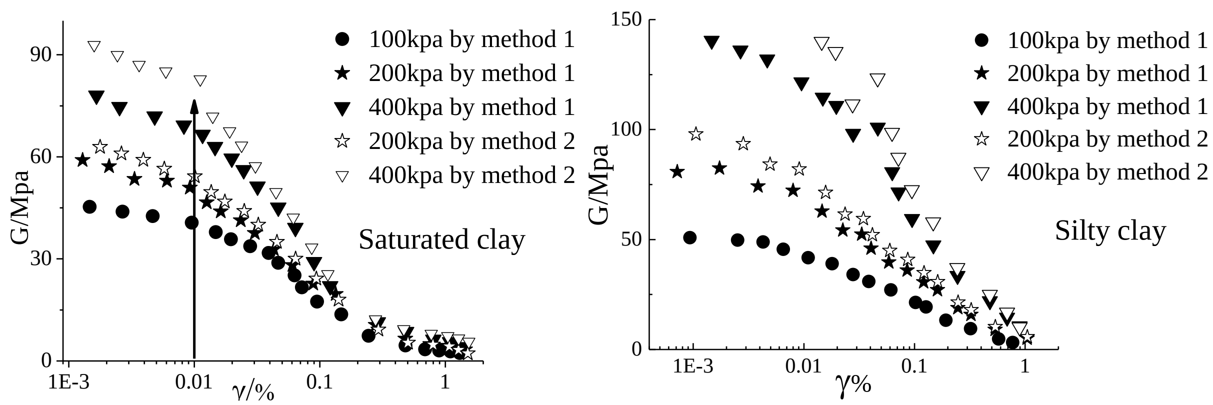

Figure 3: Variation of $G \sim \gamma$ by two test methods

G_{max} and G/G_{max} acquired by different experiments

When the maximal shear modulus is ascertained from test information, dynamic stress-strain relation is supposed to meet the Hardin – Drnevich hyperbola model, which expression can be written as:

$\tau_m=\gamma_m/(a+b\gamma_m)$ (1)

Where $a=1/G_{max}$, G_{max} is the initial slope coefficient of skeletal curve; $b=1/\tau_{max}$, τ_{max} is the maximum shear stress. Through the coordinate transformation of equation (1), it can be written as:

$$\gamma_m/\tau_m = 1/G = a+b\gamma_m=1/G_{max}+\gamma_m/\tau_{max} \quad (2)$$

After $1/G_{max}\sim\gamma$ linear relation is acquired, the initial slope coefficient of skeletal curve can be gotten as G_{max} by taking reciprocal of the straight line intercept. When ascertaining the maximal dynamic shear modulus in this paper, the dynamic shear stress-shearing strain hyperbola of small strain amplitude being mainly supposed as reference, the maximal dynamic shear modulus G_{max} is acquired by taking reciprocal of the straight line intercept after linear fitting, using the $1/G\sim\gamma$ straight line with shearing strain $\gamma<3\times10^{-4}$(the $1/G\sim\gamma$ measured by experimentation is shown as Fig.4). At the same time the other should be taken: take the dynamic shear modulus directly when $\gamma<2\times10^{-5}$ as the maximal dynamic shear modulus G^*_{max} in the $G\sim\gamma$ relation curve.

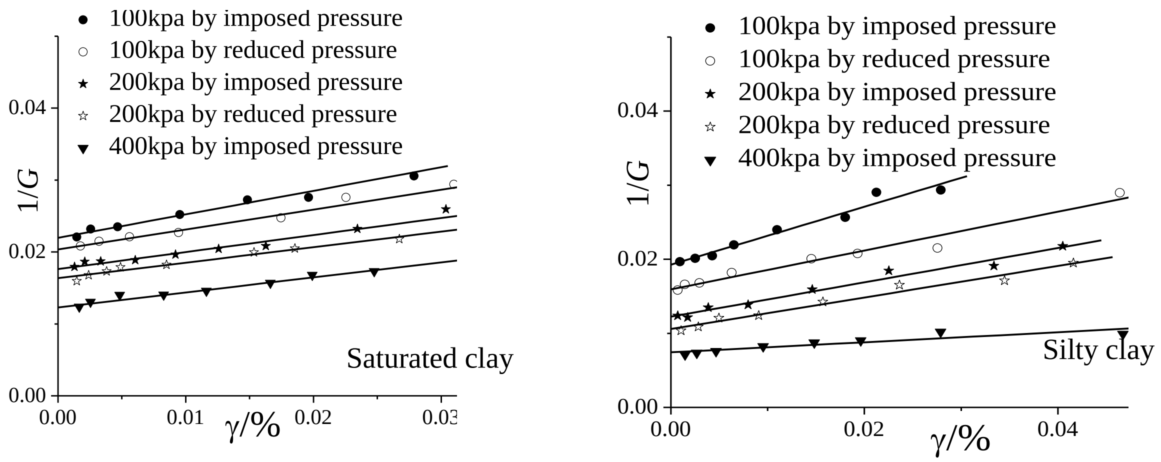

Figure 4: Fit linear plot of $1/G\sim\gamma$ curve

The maximal dynamic shear modulus taken by two different experimentation under the condition of imposed and reduced are shown as Table 2 and table 3, from which it can be seen that the dynamic shear stress-shearing strain relation satisfies Hardin-Drnevich hyperbola model in small strain amplitude ($\gamma<3\times10^{-4}$) and it is reliable to get the maximal shear modulus G_{max} and G^*_{max} by increasing the measuring accuracy of small strain. It also can be found in table 2 and Table 3 that reduced can decrease the shear modulus of clay and silty clay which is a little higher than that of imposed with the same confining pressure and the heavier reduced is, the greater the differences of shear modulus between imposed and reduced is.

Table 2: Result of $1/G\sim\gamma$ with two soils

Clay	single clay sample imposed			single clay sample reduced	
p'_{m0} /kPa	100kPa	200kPa	400kPa	200kPa	100kPa
a /MPa^{-1}	0.0220	0.0176	0.0123	0.0164	0.0204
b /MPa^{-1}	0.3273	0.2370	0.2091	0.2157	0.2765
Gmax/MPa	45.45	56.81	81.30	60.98	49.02
*G*max*/MPa^{-1}	44.68	58.47	78.29	61.11	50.23
Silty clay	**single clay sample imposed**			**single clay sample reduced**	
p'_{m0} /kPa	100kPa	200kPa	400kPa	200kPa	100kPa
a /MPa^{-1}	0.01927	0.01225	0.00744	0.01058	0.01594
b /MPa^{-1}	0.3906	0.23163	0.06775	0.21276	0.26193
Gmax/MPa	51.89	81.63	134.41	94.52	62.74
*G*max*/MPa^{-1}	50.31	82.41	138.05	95.36	62.73

According to the dependency relationship between maximal shear modulus and average effective consolidation pressure due by the two experimentations, Fig.5 has already given the relation between zero dimension maximal shear modulus $G_{max}/\ p_a$ and average effective consolidation pressure $P'_{m0}/\ p_a$ of clay and undisturbed silty clay after normalization in standard atmosphere pressure. It is can be seen from the picture that the dependency relationship between maximal shear modulus and average effective consolidation pressure on log-log coordinate basically presents a favorable linear relationship and the empirical formula of Janbu can be used to fitted. Here is the expression of empirical formula of Janbu:

$$Gmax = k_G * pa (p'_{m0}/pa)^{n_G} \quad (4)$$

In the formulae, p'_{m0} is the initial average effective principal stress (to the equal consolidation, initial average effective principal stress-p'_{m0} is equal to initial consolidated pressure σ_{3c}); Pa is the standard atmosphere pressure used for dimensionless k_G; k_G is shear modulus coefficient and n_G is shear modulus index. The result of the linear fitting parameters-k_G and n_G by two kinds of experimentation of two soil samples is shown in Table 4.

Table 3: Result of $1/G\sim\gamma$ by two test methods with two soils

	Clay by method 1			Clay by method 2		
p'_{m0} /kPa	100kPa	200kPa	400kPa	100kPa	200kPa	400kPa
a /MPa^{-1}	0.0220	0.0176	0.0123	0.0220	0.0159	0.0104
b /MPa^{-1}	0.3273	0.2370	0.2091	0.3273	0.2646	0.2265
Gmax	45.45	56.81	81.30	45.45	62.89	95.96
G*max	44.68	58.47	78.29	44.45	61.79	93.96
	Silty clay by method 1			**Silty clay by method 2**		
p'_{m0} /kPa	100kPa	200kPa	400kPa	100kPa	200kPa	400kPa
a /MPa^{-1}	0.0193	0.01225	0.00744	0.0193	0.0107	0.0056
b /MPa^{-1}	0.3906	0.23163	0.06775	0.3906	0.2081	0.1108
Gmax	51.89	81.63	134.41	51.89	93.15	178.57
G*max	50.31	82.41	138.05	50.11	95.08	172.35

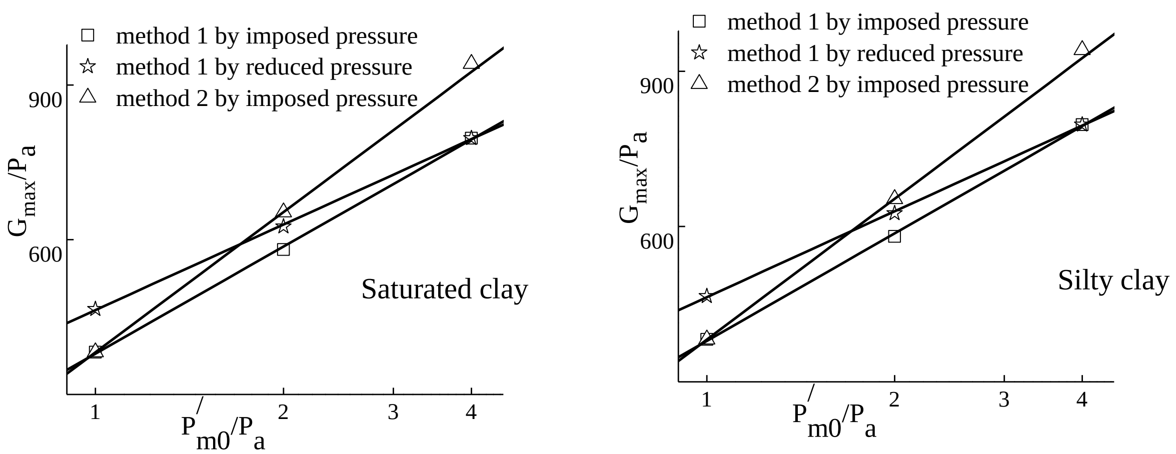

Figure 5: Variation of $G_{max}\sim\sigma_0$ by different test methods

Table 4: Parameters of k_G and n_G by two test methods

Parameters	Single sample imposed	Single sample reduced	Three samples by method 2
Clay k_G	445.09	498.98	446.68
Clay n_G	0.4046	0.3230	0.5298
Silty clay k_G	514.97	633.46	518.71
Silty clay n_G	0.68656	0.54959	0.89148

What can be seen in Fig.5 and Table 4 is that there is little influence to the empiric parameters k_G and n_G of maximal shear modulus G_{max} of two soil by different experimentations, but in details the one of silty clay is larger than saturated clay. It is suggested that the dynamic shear modulus determinates by the method of many times consolidation on one sample is familiar with the one of the method of using three single samples basically, which can make sure the reliability of experimental result and decrease the workload of experimentation and analyses.

Let the dynamic shear modulus G acquired by two methods be divided by each maximal dynamic shear modulus G_{max} and the changing law of normalization shear modulus G/G_{max} by shearing strain is shown as Fig. 6. It is can be seen from the picture that the $G/G_{max}\sim\gamma$ relation curves of different initial consolidated pressure by two methods basically fall into such a narrow banding range that the influence called by difference of experimentation is removed to a great extent. Since the scatter of points tally well with fitted curves, a suggested fitting curve can be expressed in this paper as:

$$G/G_{max} = 1/(1+a\gamma)^{b} \quad (5)$$

Clay: $G/G_{max} = 1/(1+28.22\gamma)^{0.7974}$

Silty clay: $G/G_{max} = 1/(1+37.28483\gamma)^{0.6493}$

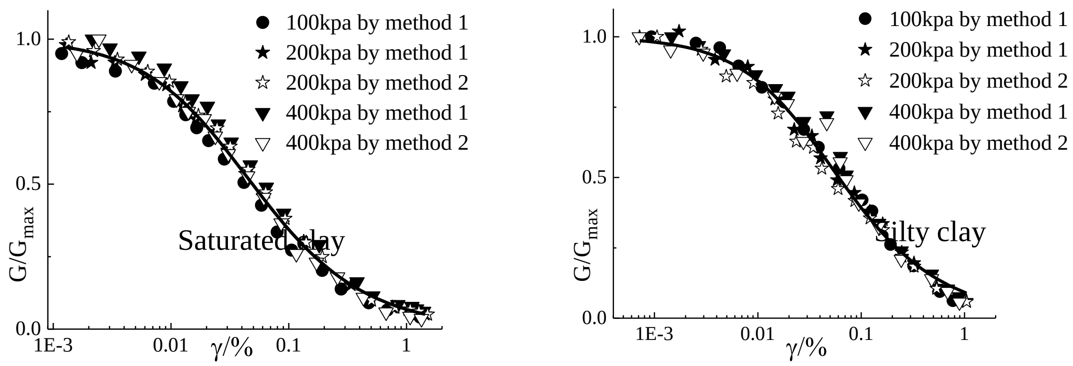

Figure 6: Variation of $G/G_{max} \sim \gamma$ by two test methods

ANALYSIS OF DAMPING RATIO RESULTS

The ξ~γ relation curve of single sample

Damping ratio of soil can express the viscous behavior of soil and the damping ratio-ξ can be gotten from the area of hysteretic loop curves and the triangle area below connection between origin point and maximal amplitude value point, that is, the ratio of coefficient of damping and critical coefficient of damping. It is hardly to perfectly fit the complicated changing law of damping ratio and shearing strain with Hardin-Drnevich and Davidenkov model, according to which the logarithmic formula used in this paper fit well:

$$\xi = \xi_{\max} - \frac{\xi_{\max} - \xi_{\min}}{1 + (\gamma / a)^{b}} \tag{6}$$

In the formulae, ξ_{min} is the least damping ratio; ξ_{max} is the maximal damping ratio; a and b are match parameter of experimentation.

It can be seen in Fig.7 that neither of clay or undisturbed silty clay is affected particularly by initial consolidated pressure, but there is still a trend of damping ratio reducing with increase of confining pressure. The reason that the damping ratio ξ reduces with the increase of consolidation pressure at the same shearing strain level could be thought that when consolidation pressure is increasing, the inter-granule touch of samples come to a trend of more and more tighter, and propagation paths come to more, due to which the energy loss reduces in spreading process and the samples stiffen, that is, the damping ratio ξ expressing how much of energy loss decreases. When $\gamma \leq 10^{-5}$, the dynamic damp changes a little to a constant; when $\gamma > 10^{-5,}$ clay and silty clay begin to express obvious non-linearity but very large elasticity and the microstructure residual deformation of two soil samples doesn't appear or appear a little; with the increase of shearing strain ($\gamma \geq 10^{-4}$) the non-linearity and inelasticity characteristics of clay and silty clay keep increasing. It is shown from the changing law of damping ratio expressing how much of energy loss increasing with shearing strain increasing that the stress-strain relation of saturated clay and undisturbed silty clay on research confirm the general rule of nonlinear elasticity and hysterics quality. The damping ratio ξ fitting result of two soil samples by experimentation of many times consolidation to one sample, respectively, is shown in Fig.7 and Table 5.

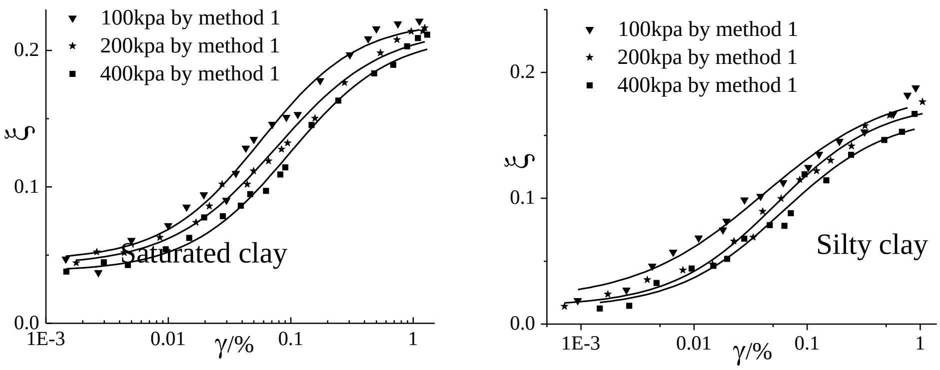

Figure 7: Variation of $\xi\sim\gamma$ of single sample with three pressures

Table 5: Result of $G/G_{max}\sim\xi$ with two soils

	Clay			Silty clay		
Confining pressure	100kPa	200kPa	400kPa	100kPa	200kPa	400kPa
a	0.0569	0.0771	0.0979	0.0411	0.053	0.0611
b	1.095	1.0011	1.0562	0.7714	0.9408	0.9222

The normalization ξ/ξ max~γ relation curve of single sample

As one of those important curves to express soil dynamic property, $\xi/\xi_{max}\sim\gamma$ curve is shown in Fig.8 from which it can be seen that all the testing point fall into a narrow banding area. Since the scatter of points well tally with the fitted curve, the fitted curve can be expressed as:

$$\xi/\xi max = a1*(\gamma/(1+a2*\gamma))^{m} \quad (7)$$

Clay $\xi/\xi_{max} = 1.431*\ (\gamma/(1+2.039\gamma))^{0.3354}$

Silty clay $\xi/\xi_{max} = 1.353*\ (\gamma/(1+1.737\gamma))^{0.3148}$

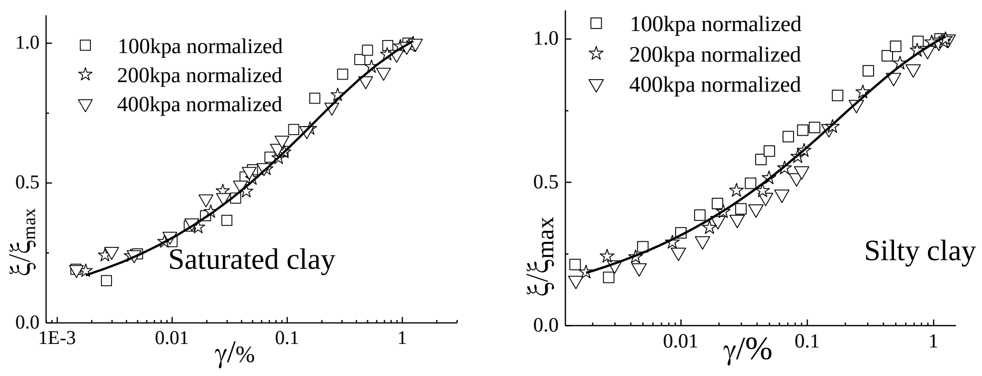

Figure 8: Variation of $\xi/\xi_{max}\sim\gamma$ by normalized

CONCLUSIONS

In this paper the method of acquiring *G* and *ξ* through changing confining pressure (including imposed and reduced pressure) on single hollow cylinder sample is compared with the method of the conventional test by different respective confining pressure on different samples:

(1) Although the result of dynamic shear modulus by multiple consolidations on single sample is a little lower than that by respective consolidation on three single samples, it is still reliable to adopt the experimentation of multiple consolidations on one sample. In this paper, for the trial curves of two methods are so closed. To use such a method as mentioned above could save amount of sampling, solve the problems of soil texture uniformity and supply a lot of advantages on base of reliable experimental result.

(2) It is shown that the dynamic shear modulus measured with impose and reduce pressure. The G and G_{max} decreased as the reduction of consolidation pressure and the gradient of reducing is smaller than gradient of imposition.

(3) The experimental result gained by continuance consolidation on single sample of clay and silty clay is satisfied, since the $G/G_{\mathrm{max}} \sim \gamma$ and $\xi/\xi_{\mathrm{max}} \sim \gamma$ after normalization of two soil samples both fall into a narrow range basically.

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