Experimental study on bidirectional and torsional cyclic loading under different initial stress states in clay

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ABSTRACT :

Before subject to complex cyclic loading induced by seismic loading, the initial stress conditions of soil element beneath the foundation under the structures generally complicated. The principal stresses of soil element under the different locations of structure are usually anisotropic and acted with bidirectional. In order to simulate dynamic behavior of saturated clay under complex stress path considering the combined effects of both initial consolidation condition and seismic loading, bidirectional and horizontal cyclic tests are conducted for anisotropic consolidation condition under different initial orientation of principal stress. The apparatus for static and dynamic universal tri-axial and torsional shear soil testing is employed to perform cyclic coupled vertical and torsional shear test in initial orientation of 0°, 45°, and 90° induced by bidirectional shaking and cyclic torsional test. Uniform and reproducible cohesive specimens having a specimen shape of hollow cylinder were obtained using vacuum suction method. The effect of initial orientation of principle stress axes on dynamic strength behavior and pore water pressure evolution of bidirectional cyclic tests and torsional cyclic tests is systematically investigation through a number of soil tests. Based on the experimental results, it was shown that the dynamic strength of saturated clay with bidirectional was less than the torsional cyclic loading under identical initial orientation of principal stress. In order to reflect the variation of water pore pressure with different stress states, the method of acquiring pore water pressure which was getting stable after ceasing coupling cyclic loading was adopt.

KEYWORDS: saturated clay, complex stress, bidirectional, dynamic strength, pore water pressure

1. Introduction

Previous studies of the effect of shear stresses on the dynamic behavior of clay have only considered the seismic loading condition corresponding to transverse earthquake motion. When subjected to seismic loading induced by longitudinal and vertical components of earthquake motions, the influence of the bidirectional loading had been importance on deformation and strength behavior of clay, which is not known well and caused engineering problem frequently (Qian et al., 1982). Practically the initial stress state beneath the foundation usually is of anisotropy. Moreover, the initial stress states of soil element located at different parts are rather sophisticated. The initial principal stresses of soil element are not equal generally on three directions under the initial consolidation condition. The large orientation of major principal stress with respect to vertical direction α_0 changes from 0° to 90°. It is necessary to adopt the experimental apparatus that can control the initial orientation of principal stress consolidation conditions and use it available for simulating tests which model multidirectional loading conditions.

The purpose of this paper is to present the results of a laboratory study of the behavior of clay subjected to bidirectional cyclic and torsional cyclic loading condition under different initial stress states. In order to perform the shear test under complex initial stress and physical conditions, an intensive effort has been made by the Institute of Geotechnical engineering, Dalian University of Technology to establish the soil static and dynamic universal triaxial and torsional shear apparatus (Guo *et al*. 2003), which was jointly designed by Dalian University of Technology and Seiken Corp., Inc., Japan. This apparatus enables to reproduce the complex initial stress condition and simulate the multidirectional cyclic loading. In order to understand effect of initial orientation of stress on strength and deformation of dense sand, a series of undrained cyclic torsional tests were carried out by Sato (1999). The multidirectional direct simple shear behavior of soil has been investigated by Don (1993), Ross (1995). The effect of the bidirectional loading on the strength of sand through using a hollow cylindrical trosional shear test was investigated by Ishihara *et al.* (1983). More comprehensive studies on this subject have been done by Wang *et al.* (1994), Fu *et al.* (2000) on silt and Miyun sand by means of a specially designed flexible shear test apparatus. The influence of orientation of initial principal stress of loose sand under bidirectional coupling shear test has been a central theme of the investigations by Guo *et al.* (2003).

As the current research situation at home and abroad, the present subject investigated is given priority to sand. But so far reports on the effect of initial orientation of principal stress as well as multidirectional loading on the undrained behaviors of clay are rare. Furthermore, comprehensive and systematic analyses on dynamic strength and pore water pressure characteristics of remolding clay subjected to multidirectional cyclic and torsional cyclic loading condition test were carried out. The present paper describes the results of tests program conducted on clay which simulates the seismic stress condition at representative element within the foundation of structure. Tests were performed at vary α_0 angles using saturated clay to determine the influence of the angle between the longitudinal and vertical components of stress loading and shear stress. The improved method of specimen preparation, the logic of automated control, as well as typical test results are presented in detail.

2. SAMPLE PREPARATION AND TEST METHOD

*2.1Sampling preparing and test apparatus*s

Due to the difficulty of obtaining uniform saturated clay specimen, the research on the bidirectional cyclic and torsional cyclic undrained shear behaviors of clay have not been system investigated. The material used for these experimental studies is the remolded clay. Despite the versatility of initial principal stress direction test, lots of problems are still identified with respect to testing procedure and the interpretation of test data. First of all, since thin wall hollow cylindrical specimens need to be used, natural soil specimens are very difficult to employ. Most undisturbed natural clay specimens have low potential of uniformity of stress and strain during loading is another major difficult. Since undisturbed clay sample is short of quantity and impossible homogeneous, the issue about it has only a little test data which disperse on value by Wang *et al*. (2000). The high potential of uniformity of stress and strain in the specimen during loading is another concern by Sayao *et al*. (1991), and the non-uniformity can be exacerbated by using non-homogenous disturbed specimens. Therefore, obtaining reproducible and homogeneous clay specimens is critical for the success of complex testing.

The hollow cylindrical specimens used in this study are prepared by using the improved vacuum suction technique, at one time reported by Yan (1991). With this technique of prepare batch homogeneous properties clay specimens for soil test, which clear up the non-uniformity of soil, also ensures the comparison between similar stress history and experimental data as well. At first, the clay powder is mixed with de-air and de-ionized water at a water content of 55.1 % as well as density of 1.41 g/cm^3 and through 14 days and nights vacuum suction, then the uniform saturated clay specimens that satisfying test requirement are prepared. Specimens made by using the vacuum suction technique are composed of equal element with high saturation level and the variation of water content is less than 2%. In order to ensure a high quality uniform of the specimens, significant cares are taken during the development stage of testing related to clay specimen preparation, its uniformity and B value verification. It easily to be trim into solid cylindrical or hollow cylindrical specimen, also the test data has high comparability and repeatability proved by static triaxial tests. It took approximately 14 days for specimens to be prepared, as shown in a typical settlement history plotted in Figure.1. The basic physical property indices of the samples are listed as Table 2.1.

Table 2.1 Physical property of the clay and silty clay samples

	ρ/(t·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

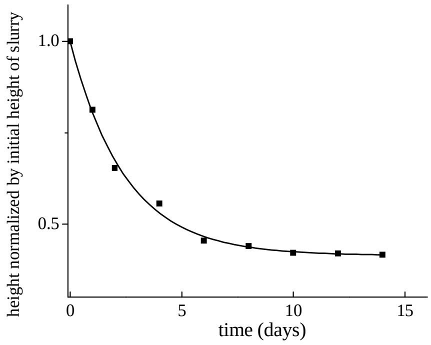

Figure 1 Settlement history of slurry in terms of clay height

For the typical hollow cylindrical specimen used in the study, the outer and inner diameters of the specimens are D=70 mm and d=30 mm respectively and the height is H=100 mm. Both top and bottom drained is allowed to shorten the duration of primary consolidation. In order to reduce the necessary time for consolidation and pore water pressure equalization, filter paper is used around the outer surface of the specimen to provide radial drainage paths. Saturation of the sample is fulfilled by pouring de-air water and by exerting back pressure. This is necessary to saturate the interface of specimens and inner and outer membranes (since the clay sample is already fully saturated at the end of vacuum suction technique). The consolidation completion criteria of clay follow the Standard for Civil Engineering Experiment (SL237-1999).

2.2. Illustration of Test Apparatus

The soil static and dynamic universal triaxial and torsional shear apparatus in laboratory used for the experiments is composed of five components including main unit, air-water unit (air compressor and vacuum pump), analogue control unit, data acquisition and automatic control system and hydraulic servo loading unit (hydraulic actuators and hydraulic supply). The details concerning this comprehensive system were given by Luan *et al.* (2003).
This apparatus can be simulate complex initial stress states with different combinations of the coefficient of intermediate principal stress and orientation of initial major principal stress. The soil static and dynamic universal triaxial and torsional shear apparatus enable to simultaneously impose and individually control axial pressure W_0 and torque M_{T0} as well as outer chamber pressure p_o and inner chamber pressure p_i. Also different combinations of these components can be fulfilled. Therefore the consolidation and loading paths under different complex stress condition of soils can be implemented.

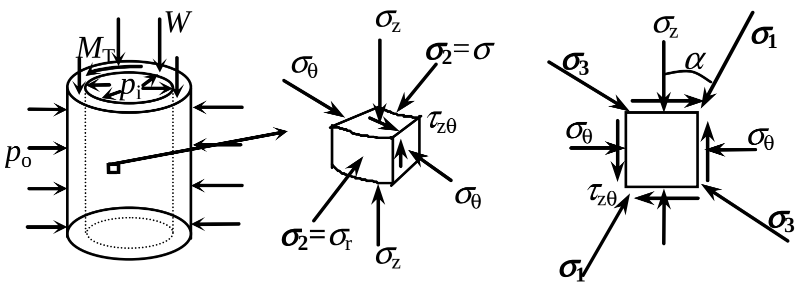

Figure 2 Stress state of soil element in hollow-cylinder sample

By this system, both inner and outer chamber pressure, as well as individual components of static torque and axial force can be independently imposed on soil sample and controlled. Accordingly, lots of complex consolidation of coefficient of intermediate principal stress and orientation of initial principal stress can be simulated. A typical stress of soil element in hollow cylindrical sample is illustrated in Figure 2.

2.3 Test Procedure

In these experiments, the three-direction anisotropic consolidation stress state is achieved by simultaneously controlling axial pressure W, torque M_T, outer chamber pressure p_o and inner chamber pressure p_i as well as the combination of these components. For the sake of investigate the influence of multidirectional cyclic tests and torsional cyclic tests under anisotropic consolidation condition, three type tests of α_0=0°, 45°and 90° were performed. The applied loading is given in Table 2.2. After saturation and consolidation, cyclic sinusoidal wave load were applied in the vertical direction and horizontal direction. The cyclic bidirectional shear tests in which the amplitude of the cyclic deviatoric stress originated from the deviation of normal stress and shear stress keeps unchanged. In order to examine the effect of the orientation of principal stress, the orientation angle of major principal stress α_0 with respect to the vertical direction defined as following are employed in this paper

$$\alpha_0 = \frac{1}{2}\arctan\left(\frac{2\tau_{z\theta}}{\sigma_z - \sigma_\theta}\right) \tag{2.1}$$

Where σ_z and σ_θ are axial and circumferential mean normal stress while $\tau_{z\theta}$ is mean shear stress induced by torque in the hollow cylinder sample.

Table 2.2 Combinations of applied loads during consolidation

α_0	p_i / kPa	p_o / kPa	W_0 / kN	M_{T0} / (N×m)
0°	116.67	93.86	0.118	0
45°	100	100	0	2.07
90°	83.33	107.14	−0.118	0

3. ANALYSIS OF TEST RESULT

3.1 Effect of α_0 on Dynamic Strength

The bidirectional cyclic tests are characterized by the combination of the deviatoric of normal stress and the shear stress and torsional cyclic tests are characterized by the shear stress under anisotropic consolidation condition simulate the seismic. In this paper, the author adopt the maximum shear stress amplitude τ_f as shown in the following equation(Sato *et al.*, 1999), which acts as the dynamic strength in the specific bidirectional cyclic test.

$$\tau_f = \sqrt{\left(\frac{\sigma_d}{2}\right)^2 + \tau_d^2} \tag{3.1}$$

Where σ_d and τ_d are cyclic normal deviatoric stress and cyclic shear stress.

The failure criterion regarding the clay usually takes as 5 % double amplitude torsional strain or 5 % sum of single amplitude and residual accumulative strain in the torsional cyclic tests. However, the failure criterion of double amplitude strain or the one which advised by Andersen (1988) can not consider the synthetically influence of axial and horizontal deformation. Consequently, the generalized shear strain (Fu *et al.*, 2000) reaching a certain constant as the failure criteria was adopted. Whereas, this criteria can not consider the influence of negative strain and the fluctuation range of generalized shear strain is rather large.

Accordingly to the stress and strain relationship under bidirectional cyclic test, the author was recommended the equation (3.2) as the synthesis strain of the failure criterion for the multidirectional loading test. It was shown that synthesis strain for clay was reconsidering the integrative effects of torsional shear strain and normal deviatoric strain as well as cyclic strain and accumulative strain. Meanwhile, the synthesis strain fail criterion was fit for the failure criterion of rotation of principal stress axe under complex initial orientation of principal stress.

$$\gamma_{gs}=\sqrt{(\frac{\varepsilon_{\max}+\varepsilon_{\min}}{2})^2+(\frac{\gamma_{\max}+\gamma_{\min}}{2})^2}+\frac{\sqrt{2}}{3}\sqrt{\frac{9}{2}(\varepsilon_{\max}-\varepsilon_{\min})^2+\frac{3}{2}(\gamma_{\max}-\gamma_{\min})^2} \tag{3.2}$$

In which γ_{gs} is the synthesis strain; $\varepsilon_{\max}$ and $\varepsilon_{\min}$ is the maximum and minimum axial strain of the cyclic hysteretic loop; $\gamma_{\max}$ and $\gamma_{\min}$ presents the maximum and minimum shear strain of the cyclic hysteretic loop, respective. The two parts of the right side of the equation is independent average residual deformation and cyclical deformation, which due to the combined effect of negative deviation and shear strain.

The dynamic strength of remolded cohesive soil under multidirectional cyclic test is generally determined by synthesis strain. The dynamic strength in this study is taken as the 5% amplitude synthesis strain, and it has similar properties of dynamic strength determined by other criteria. The dynamic strength takes as 5 % sum of single amplitude and residual accumulative strain in the torsional cyclic tests. Figure. 3 shows the effect of α_0 on the variation of the dynamic stress ratio with the number of cycles caused by γ_{gs}= 5% and γ = 5%. The logarithmic scale of the number of cycles is used to show the variation at the initial cycles of the tests. It should be noted that the dynamic stress was calculated without correction for the area change that occurs during the test.

Figure.3 summarizes the influence of anisotropic consolidation on the bidirectional cyclic tests and torsional cyclic tests. Based on the experimental results, it was shown that the dynamic strength of saturated clay on bidirectional was less than the torsional cyclic loading under identical initial orientation of principal stress. It was found that the dynamic strength with the identical α_0 have increased 34 % on the bidirectional cyclic tests and torsional cyclic tests, approximately. Figure.3 also indicates that the dynamic stress decreases with the increase of orientation of initial principal stress α_0 from 0° to 90° for a given number of cycles, i.e., the small the α_0 becomes, the large the dynamic strength will be, whereas the effect of orientation of initial principal stress α_0 gradually diminishes small when the number of cycles is large enough. As the α_0 increases from 0° to 90°, the initial major principal stress that acting on the horizontal plane changes in correspondence into the initial minor principal stress. For the same cyclic number, the dynamic strength with different orientation of initial principal stress has been compared to the dynamic strength with 0°. It found that the dynamic strength with the α_0 of 45° and 90° have reduced 18 % as well as 29 % approximately, respectively. The reduced gradient of dynamic strength reduces in correspondence to an increasing α_0, that is to say the influence of α_0 to the dynamic strength of clay with principal stress directions diminishes.

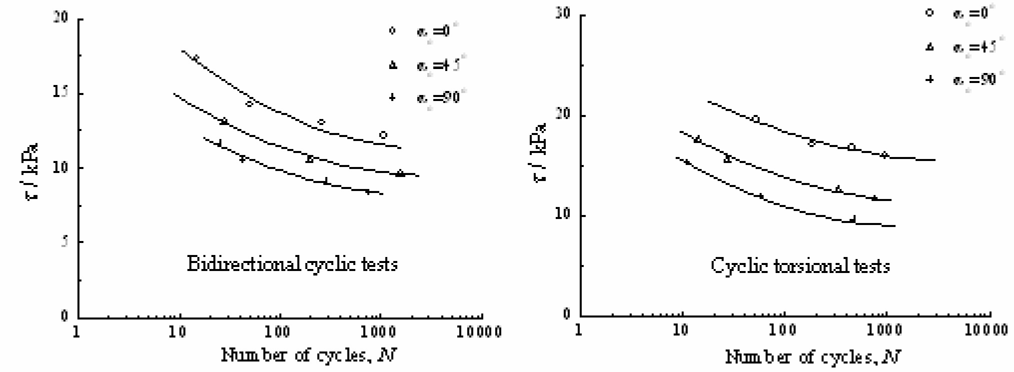

Figure 3 Effect of orientation of initial principal stress α_0 on dynamic strength on bidirectional cyclic tests and torsional cyclic tests.

4.2 Effect of α_0 on pore water pressure

One of the significant factors to influence of deformation and strength characteristics of clay with cyclic loading is the development of water pore pressure. Also, the cyclic water pore pressure for saturated clay is a significant factor which affects the stability on structure. Hence, the evolution of pore water pressure for saturated clay under orientation of initial principal stress α_0 is important to be investigated. The water pore pressure has hysteretic phenomenon for clay as measured under cyclic loading, and it is believed that gradient of axial and radial of water pore pressure induced by it. However， the measurement of water pore pressure is proceeded at the bottom of the hollow specimen. Apparently, the measurement of water pore pressure can not reflect the truth increasing of water pore pressure completely under the cyclic loading. Thus, consulting the measuring method according to Yasuhara (1994), when undrained coupling cyclic loading in cohesive soil is terminated at failure states, a continuous measurement of acquiring pore water pressure which was getting stable after ceasing coupling cyclic loading was adopt.

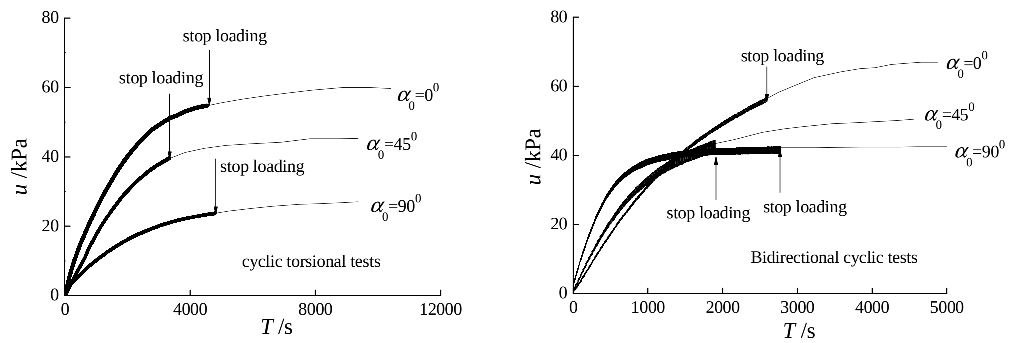

Figure 4 variation of pore water pressure under different orientation of initial principal stress α_0 on bidirectional cyclic tests and torsional cyclic tests.

The effect of α_0 on the typical water pore pressure versus the time with approximate number of cycles is shown in Figure 4. As shown in Figure 4, the initial fluctuating section of water pore pressure is the cyclic water pore pressure in process of coupling cyclic loading. The post-curve section is the water pore pressure that is continuous measured by the clay sample when the cyclic loading stopped. Apparently, the post-curve water pore pressure still has an increasing stage until it comes up to stabile value. Hence, it is prefer to adopt the method recommended by author as mentioned above, which can reflect the increasing of pore water pressure under on bidirectional cyclic and torsional cyclic loading with different α_0 better. The fluctuating water pore pressure represent a trend of average cumulative water pore pressure that continuous increased and separately rises, and the amplitude of cyclic pore pressure is small.

Figure 4 also show that on the bidirectional cyclic tests and torsional cyclic tests, the α_0 has an important influence on the cyclic cumulative pore water pressure. It also indicates that the pore water pressure with the increasing of α_0 for a given time, i.e., the higher the α_0 becomes, the smaller the stopping pore water pressure will be, whereas the smaller the stable value of water pore pressure will be.

4 CONCLUSIONS

Bidirectional cyclic tests and torsional cyclic tests were performed using soil static and dynamic universal triaxial and torsional shear apparatus in order to approximate the loading conditions under complex initial stress conditions to simulate seismic loading induced by parallel and perpendicular cyclic loading, respectively. Through a comprehensive study of the experimental test data, the effect of α_0 on dynamic strength and pore water pressure on multidirectional and torsional cyclic tests were examined. The conclusions can be summarized as below.

(1) The hollow cylindrical specimens used in this study are prepared by using the improved vacuum suction technique, which is significant for the success of the testing. It ensures the comparison between similar historical stress and experimental data as well with this technique.

(2) It was shown that a general strain fail criterion for clay was recommended for considering the integrative effects of torsional shear strain and normal deviatoric strain as well as cyclic strain and accumulative strain. The dynamic strength in this study is taken as the 5% synthesis strain on bidirectional cyclic tests and 5 % sum of single amplitude and residual accumulative strain on the torsional cyclic tests. As the orientation of initial major principal stress exhibits increased, the dynamic strength of saturated clay decreased when the hollow specimen subject to complex cyclic loading and the dynamic strength of saturated clay with bidirectional was less than the torsional cyclic loading under identical initial orientation of principal stress.

(3) In order to reflect the variation of water pore pressure with different stress states, the method of acquiring pore water pressure which was getting stable after ceasing coupling cyclic loading was adopt. Based on the experimental results, it was shown that the pore water pressure of saturated clay on bidirectional cyclic tests were more than the torsional cyclic loading under identical initial orientation of principal stress. These findings will provide more information about multidirectional in saturated clay, and can be used as reference for improving design of seismic structure and foundation subjected to complex loading.

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