Weakening Characteristics of Soft Clay Foundation under Earthquake

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Abstract. The dynamic triaxial test is carried out by the dynamic cyclic shear equipment GDS to determine the strength of soil after earthquake cyclic loading. The consolidation pressure is determined according to the in-situ stress state of soil samples. The samples are loaded with sinusoidal periodic loads of different amplitudes at a fixed frequency, with the failure standard of achieving the same final residual strain. Compared with the static triaxial test results, we can determine the strength weakening of soft clay foundation with different depths under earthquake load, which can provide a reliable reference for engineering problems such as the bearing capacity of pile foundation in soft clay.

1. Introduction
Soft clay soil is widely distributed in coastal cities and other areas, and coastal areas are mostly economically developed areas with plenty of infrastructure construction projects. The strength of foundation soil may be reduced by earthquake cyclic loading. Therefore, the influence of dynamic loads such as earthquake on the bearing capacity of foundation and its structures such as pile foundation should be evaluated[1-3].

For the study of strength weakening under cyclic loading, scholars at home and abroad have made certain achievements. For example, Wang et al.[4] obtained the law of soil stiffness softening through stress control cyclic triaxial test on normally consolidated saturated soft clay. However, most of studies mainly focus on the condition of static deviatoric stress applied after isotropic consolidation, which is different from the actual consolidation state of soil, while the consolidation state has a significant impact on the strength characteristics of soil under cyclic load[5].

Through dynamic triaxial simulation of reciprocating vibration such as earthquake, the strength loss of soil at different depths under the action of different reciprocating dynamic stress is studied, and its residual strength is determined. Thus, the strength reduction degree under the cyclic action of dynamic load is analyzed, which can provide a reliable reference for engineering problems such as evaluating the bearing capacity of pile foundation in soft clay.

2. Test principle
Because the dynamic strength of cohesive soil is inversely related to the number of loading cycles, it is also related to the initial shear stress if there has initial shear stress. If the soil sample is under the same initial shear stress τ₀, and then continuously applied with shear stress in different amplitude τₖ for N cycles, the greater the shear stress is, the greater the shear strain after loading; if the loading times are less, the disturbance effect is small, and the loading rate effect will increase the strength which may be greater than the strength of static test. If the number of loading cycles is changed, the dynamic stress-strain curve and shear strength will change accordingly. The more the loading cycles...
are, the smaller the residual shear strength of soil is. Periodic loading makes the structure of soil sample be destroyed and softened, and then the strength will be reduced. The test results show that the greater the initial shear stress, the smaller the strength under cyclic loading, and the dynamic strength \( \tau_0 \) is greater than the static strength when the loading times are less, as shown in Figure 1.

![Figure 1. Relationship curve between shear stress and shear strain](image)

(a) Different number of loading cycles (b) Different initial shear stress

Under cyclic loading, smaller loading rate may increase the strength of saturated soft clay, while periodic disturbance may cause strength decrease, which are related to water content and saturation of soft clay, both affecting the dynamic strength change of soil.

When using dynamic triaxial to simulate earthquake action, in order to apply the results of equal amplitude load to actual earthquake stress, Seed et al. \[^{[6]}\] proposed that 0.65 times of the actual peak value of earthquake stress should be taken as the amplitude of equal amplitude cyclic stress, and the number of cycles of equal amplitude load should be determined according to the magnitude of earthquake. However, the experimental results of residual deformation of soil and low-level uneven earthquake subsidence of buildings are quite different from the actual ones. For the strength loss test of soil under cyclic load, the strength loss of soil at different depths after the occurrence of a certain amount of residual strain under cyclic load should be studied, which has more practical significance for practical engineering problems. Therefore, a sinusoidal periodic load with a frequency of 1Hz is used to load the samples at different amplitudes to achieve the same final residual strain for each sample. Finally, the strength loss degree of soil samples after vibration is tested.

3. Test instruments and soil samples

The test is carried out by the dynamic cyclic shear equipment GDS (Global Digital System, hereinafter referred to as GDS), as shown in Figure 2. The equipment can monitor the whole test process in real time, collect and store data at high speed, with high precision and reliable results, which is a set of digital test equipment. The system consists of a pressurization system, a control system and a measuring system. The pressurization system consists of a back-pressure controller, an axial pressurization device and a confining pressure controller. Deformation, pressure and other data collected by sensors are stored in GDS-DCS, and then transmitted to computer processing control system through high-speed USB interface to complete test control, data acquisition and data processing.

The test soil samples are undisturbed soil samples taken from a wharf in Shenzhen. The basic parameters of soil samples are shown in Table 1.
4. Dynamic triaxial test for simulating earthquake action

The undisturbed soil sample is a cylinder with a diameter of 39.1 mm and a height of 80 mm. In the process of field sampling, transportation and laboratory preparation, the internal structure of soil will be damaged in varying degrees. Firstly, the soil samples are consolidated in the pressure chamber for 24 hours, and then the axial static load and corresponding dynamic load are applied. The consolidation pressure should conform to the in-situ stress state of the soil sample to simulate the isotropic consolidation under the self-weight stress.

For the static load (CU) test, different consolidation pressures are applied to each group of samples, and then the prepared samples are placed in the pressure chamber for consolidation. After consolidation, the drain valve is closed and the axial static load is applied. The loading rate is controlled at 0.1% ~ 0.5% strain per minute. When the deformation of soil sample reaches 15% ~ 20% of the initial height of soil sample (80mm), it is considered that there is shear failure of the sample. According to the deviatoric stress ($\sigma_1 - \sigma_3$) and consolidation pressure at failure of the soil sample obtained from static load test, the ultimate stress circle can be made in the stress space. According to the common tangent of four ultimate stress circles, the original triaxial strength of the sample can be obtained.

For the dynamic load (CU) test, after consolidation, the drain valve is closed, then the axial sinusoidal load is applied immediately, with the vibration frequency of 1Hz and the amplitude of $\sigma_d$. When the residual strain of the soil sample is 5%, the dynamic load should be stopped and the undrained static triaxial shear (CU) test is carried out. The loading rate of undrained static triaxial shear is 0.1% ~ 0.5% strain per minute. After the deformation of soil sample reaches the specified failure standard, the residual strength of soil sample under dynamic load is obtained.

Comparing the consolidated undrained strength index obtained from static load test and the residual strength after the dynamic load test of the same soil sample under the same consolidation condition, the soil strength reduction rate $\gamma$ is calculated as follows:

$$\gamma = \left( \frac{\tau_{fs} - \tau_{fd}}{\tau_{fs}} \right)$$

(1)

Where: $\tau_{fs}$ is the original static triaxial strength of soil sample; $\tau_{fd}$ is the residual strength of soil sample after vibration.
5. Test result
Under cyclic loading, the stress-strain relationship of saturated soft clay is represented by a series of hysteretic loop curves. The axial strain increases and the backbone curve gradually inclines with the increase of the number of cycles, that is, under the action of dynamic load, the soil softens and the undrained strength decreases. The typical stress-strain curve of the soil sample under dynamic load is shown in Figure 3.

![Stress-strain hysteresis loop](image)

Figure 3. Stress-strain hysteresis loop

The comparison diagram of static triaxial test results of undisturbed soil samples and the corresponding soil samples after dynamic load vibration is shown in Figure 4.

The same dynamic load $\sigma_d$ is applied to soil samples with different consolidation pressures to determine the strength of the soil in static triaxial tests before and after vibration. The strength reduction rules of soil samples under dynamic load are obtained by changing the dynamic load $\sigma_d$ and repeating the above tests, as shown in Table 2 and Figure 4.

![Comparison of static triaxial strength before and after vibration](image)

Figure 4. Comparison of static triaxial strength before and after vibration of soil samples

| dynamic stress (kPa) | consolidation stress (kPa) | original strength (kPa) | residual strength (kPa) | strength reduction rate |
|----------------------|---------------------------|------------------------|------------------------|------------------------|
| 18                   | 30                        | 24                     | 17                     | 0.708                  |
|                      | 70                        | 28.3                   | 24                     | 0.848                  |
| 15                   | 30                        | 21                     | 16                     | 0.762                  |
|                      | 50                        | 24.2                   | 19                     | 0.785                  |
|                      | 90                        | 30.4                   | 28                     | 0.826                  |
| 13                   | 30                        | 22                     | 18                     | 0.818                  |
|                      | 50                        | 24.2                   | 21                     | 0.876                  |
|                      | 70                        | 28.3                   | 26                     | 0.919                  |
According to Table 2, the shear strength reduction law of soft clay at different depths under earthquake action can be obtained, as shown in Figure 5.

![Figure 5. Reduction law of soil strength under earthquake load](image)

6. Conclusion
The dynamic triaxial test and static triaxial test are used to determine the strength of the foundation soil before and after the earthquake cyclic load, so as to determine the strength weakening of the soft clay foundation under the earthquake load. The corresponding frequency of dynamic load is selected for earthquake load to carry out the strength weakening test of foundation soil. The following conclusions are obtained.

- Different consolidation pressures are used to simulate different depths, and a certain amount of plastic strain is taken as the criterion of stopping dynamic triaxial test. Then, the static triaxial strength test is carried out to have the comparison with the static triaxial strength of undisturbed soil, so as to obtain the strength reduction rate, which gives the different weakening degree of foundation soil caused by cyclic load with different amplitude.

- Under the action of earthquake vibration, the strength of soft clay has different degrees of weakening. On the one hand, the cyclic dynamic load will make the soil produce excess hydrostatic pressure, which will reduce the strength of foundation soil; on the other hand, under the action of cyclic dynamic load, the structure of foundation soil will be damaged, resulting in the reduction of its shear strength.

- Under the same consolidation pressure, the greater the amplitude of dynamic load, the greater the shear strength reduction. The shear strength reduction curves of soft clay under different consolidation pressures are obtained through the test, which can be used to evaluate the weakening degree of bearing capacity of soft clay foundation soil under the action of earthquake and other dynamic loads.

References
[1] Airey D W, Fahey M. (1991) Cyclic response of calcareous soil from the North-West Shelf of Australia. Geotechnique, 41, 1: 101-121.
[2] Idriss, Izzat M, Singh, Ram D, Dobry, Ricardo. (1978) Nonlinear Behavior of Soft Clays during Cyclic Loading. j.geotech.eng.div.proc.asce, 104, 12:1427-1447.
[3] Sharma S S, Fahey M. (2003) Evaluation of cyclic shear strength of two cemented calcareous soils. Journal of Geotechnical and Geoenvironmental Engineering, 129, 7: 608-618.
[4] Wang J W, Cai Y, Xu C. (2007) Experimental study on degradation of stiffness of saturated soft clay under undrained cyclic loading. Rock and Soil Mechanics, 28, 10: 2138-2144.
[5] Pillai R J, Robinson R G, (2011) Boominathan A. Effect of microfabric on undrained static and cyclic behavior of kaolin clay. Journal of Geotechnical and Geoenvironmental Engineering, 137, 4: 421-429.
[6] Seed, H. B., and Chan, C. K. (1966) Clay strength under earthquake loading conditions. Journal of Soil Mechanics and Foundations Divisions, 92, 2: 53-78.