Monotonic triaxial shear strength and cyclic triaxial properties of undisturbed soft soil

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Abstract. The static and dynamic characteristics of Tianjin coastal soft soil are researched by cyclic triaxial test. For triaxial shear test, the specimens are isotopically consolidated under initial pressures of 100 kPa, 200 kPa, 300 kPa and 400 kPa, respectively; for the dynamic triaxial test, the specimens are consolidated under initial isotropic consolidation pressures of 100, 200, 300 kPa, respectively. The applied dynamic displacements are graded for each specimen, and the pore-water pressure is completely dissipated before application of next displacement amplitude. These tests show that the effective cohesion is 6 kPa and the effective internal friction angle is 26.5 degrees under consolidated undrained condition. The maximum shear modulus of soil is related to effective confining pressure, and its relationship with effective confining pressure can be expressed by JIanbu’s formula. The shear modulus of soil is related to shear strain and decreases with the increase of shear strain. Hardin-Drnevich can be used to normalize the shear modulus.

1. Introduction
Tianjin is a typical coastal city covered with deep soft soil. In order to relieve the traffic pressure, many subway projects have been built and many others are still under plan. In the design of subway, the shield segment should not only have sufficient strength, but also should meet the requirements of stability and earthquake resistance which requires earthquake resistance design. In the recent revision of the Chinese Code for Seismic Design of Buildings (GB 50011-2010, version 2016), the seismic precautionary intensity of Tianjin has been raised. In order to understand the requirements of this adjustment on the seismic design of Tianjin underground rail transit, the seismic dynamic properties of soft soil should first be determined. This paper intends to study the dynamic properties of Tianjin soft soil through dynamic triaxial tests for a purpose of providing reference for the seismic design of shield line.

2. Test preparation

2.1. Soil properties and test apparatus
The soil samples were taken from Yihezhuang of Tianjin Binhai New Area. It is grey with some silt aggregates. Its water content is 25.5%, specific gravity 2.71, dry density 1.49 g/cm$^3$, degree of saturation 83%, void ratio 0.819, liquid index 10.9 and plastic index 0.83. It is classified as silty clay.

The GDS instrument was used for this research (Figure 1). This instrument can not only accommodate conventional triaxial compression tests with control of stress and strain, but also accommodate dynamic triaxial compression test below 2 Hz. Moreover, it can simulate waveforms such as sine wave, triangular wave, rectangular wave, user-defined waveform.

2.2. Test program

The test program covers conventional triaxial shear tests (CU) and dynamic triaxial compression tests. Both tests are conducted under consolidation-undrained conditions (CU). Four specimens are used for CU tests. The initial consolidation pressures are 100 kPa, 200 kPa, 300 kPa and 400 kPa, respectively. The test procedures are as follows: a) saturate the soil specimen by vacuum pumping; b) install the specimen on the triaxial apparatus and further saturate it by back pressure saturation method. When the pore-water pressure parameter B reaches 0.98, the specimen is considered to be fully saturated; c) consolidate the specimen isotropically under different consolidation stresses, and d) shear the specimen or apply dynamic load under undrain condition.

The dynamic triaxial test are often conducted to determine dynamic characteristic indexes such as dynamic elastic modulus and damping ratio under strain below 10$^{-4}$. In these tests, the soil dynamic properties are obtained from serval specimens which is considered as totally identical. In practice, the results obtained from these “identical” samples are often highly discrete. In order to obtain reliable test data, we adopt a graded loading program, i.e. after the specimen is isotropically consolidated under certain stresses, apply unidirectional excitation of sine wave under 8 vibration amplitudes of 0.005 mm, 0.01 mm, 0.02 mm, 0.04 mm, 0.08 mm, 0.16 mm, 0.32 mm and 0.64 mm, and then further consolidate the specimen isotropically under a higher stress to conduct another excitation of 8 amplitudes. Conduct the test until all the consolidation stresses are applied.

3. Test result

3.1. Triaxial shear test

Figure 2 shows the curves of deviator stress versus axial strain for triaxial shear test. It can be seen that the curves are strain-hardening type under various consolidation pressures, and no softening is found. All the specimens reach critical state line on the effective stress path plane. The failure stress is taken as the value at 15% of the corresponding axial strain since the peak value is not obvious.
3.2. Triaxial cyclic test

In order to reduce the disturbance, the damping ratio and shear modulus of each stage are calculated from the results of the five loading cycles. The results obtained by this method are very satisfactory and easy to analyse.

The axial stress and axial displacement are measured during each stress stage. There are 3 consolidation stress stages and for each stage there are 8 loading amplitudes. For each amplitude, five cycles are applied. The vibration curve of the first-order amplitude (0.005 mm) vibration under the isotropic consolidation stress of 300 kPa is listed here as shown in Figure 3. It can be seen that under an axial sine waveform, the pore-water pressure presents a sine waveform as well as the axial force (not presented in the figure). The pore-water pressure has slight oscillation phenomenon during the exciting process. Thus, the soil response can be considered to be elastic.

\[ G_{d_{max}} = K \sigma_m' \left( \frac{\sigma_m'}{P_a} \right)^m \]  

(1)

where \( m \) is modulus number, \( K \) is material constant, \( \sigma_m' \) is the mean effective stress, and \( P_a \) is reference stress which is taken as the atmospheric pressure value. The fitting result for Tianjin soft soil is \( m=7.414, K=74.764 \), as shown in Figure 4(b).
Figure 4. Dynamic test result: (a) Dynamic shear modulus vs. shear strain; (b) Max. dynamic shear modulus vs. confining stress.

The relationship between damping ratio and shear strain is shown in Figure 5. It can be seen that the damping coefficient under all three stages of consolidation pressure is close and increases with the increase of shear strain.

Figure 5. Dynamic test result: (a) Dynamic shear modulus vs. shear strain; (b) Max. dynamic shear modulus vs. confining stress.

The relationship between shear modulus and shear strain is usually described by Ramberg-Osgood or hyperbolic model (Hardin-Drnevich formula). The former is often used to simulate one-dimensional wave propagation problem [2,3]. The latter is simple with clear parameter meaning. The shear modulus can be normalized by the maximum value under different pressures and be expressed in a hyperbolic form [4,5]:

\[ \frac{G}{G_{\text{max}}} = \frac{1}{1 + \gamma / \gamma_{\text{ref}}} \]  

where \( \gamma_{\text{ref}} = 0.091 \), it is acceptable that the fitting coefficient is \( R^2 = 0.9765 \).

4. Conclusions
This research has carried out conventional and dynamic triaxial tests on Tianjin soft soil to obtain its compression and dynamic characteristics. The test result shows that the effective cohesion of silt clay is 6 kPa and the effective internal friction angle is 26.5°. The maximum shear modulus of soil is related to effective confining pressure, and its relationship with effective confining pressure can be expressed by Janbu’s formula. The shear modulus of soil is related to shear strain and decreases with the increase of shear strain. The Hardin-Drneveich can be used to fit the shear modulus with proper fitting parameters.
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