Study on the creep behaviors of Tianjin soft clays under cyclic loading

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Abstract: A creep test of remolded Tianjin saturated silty clay under cyclic loading was carried out. The test results showed that the cyclic creep curve exhibited attenuation- stabilization characteristics. At the initial stage of cyclic loading, the creep curve was approximately sinusoidal, and the axial strain increased with creep time. At the end of cyclic loading, the axial strain remained basically the same, and the stress-strain hysteresis curves tended to coincide, indicating that the soil creep tended to be stable. The cyclic creep was composed of cumulative plastic strain and reversible strain. The reversible strain of soil was related to the dynamic stress level. The larger the magnitude of cyclic stress, the larger reversible strain was generated. At the initial stage of cyclic loading, the cumulative plastic strain increased rapidly, and as the number of cyclic loadings increased, the cumulative plastic strain gradually entered the attenuation stage and eventually reached the stable stage.

1. Introduction

With the rapid development of the coastal economy in recent years, many engineering projects have been constructed on soft clay foundations. Soft clay is characterized by high moisture content, large void ratio, low shear strength, poor permeability, and strong creep effect[1]. Under a static load, the creep rate is relatively small, whereas under a dynamic load, the deformation rate of soft clay increases significantly. In 1975, Yasuhara et al. carried out field tests on a low embankment highway built on a soft clay foundation and found that the deformation of the embankment reached 2 m five years after construction[2]. Due to the creep effect of soft soils, the deformation of railways built on a soft clay foundation in Japan reached 1 m after five years of operation[3]. After two years of operation, the accumulated plastic deformation of the Shanghai outer ring road at the Beizhai intersection reached 9 to 10 cm[4]. The above analysis shows that the soft clay foundation can undergo large deformation under the dynamic load, seriously affecting the service life and safety of engineering projects. Therefore, it is necessary to conduct in-depth systematic studies on the creep properties of soft clay under cyclic loading.
Some researchers have carried out relevant studies. Luo et al. established a boundary surface model considering the time effect based on the boundary surface constitutive model and the Mesri creep model and verified the effectiveness of the new model by comparing its results to those from the triaxial creep test of Nanjing soft soil[5]. Zhang et al. used the triaxial consolidation apparatus to study the creep deformation characteristics of saturated soft clay under complex loading. Their results showed that under cyclic loading, the time for loading and unloading to reach stable deformation decreased as the number of cycles increased. When the maximum value of the cyclic loading was smaller than the preconsolidation pressure of the soil sample, the soil sample reached the state of elastic deformation after two cycles of loading and unloading. When the maximum value of the cyclic loading was equal to the preconsolidation pressure of the soil sample, the soil sample reached the state of elastic deformation after five cycles of loading and unloading[6]. Zhu et al. investigated the deformation characteristics of Shanghai saturated silty clay under long-term cyclic loading. Their results showed that when the cyclic axial stress was less than 50% of the preconsolidation pressure, the cyclic creep of the saturated soft clay was divided into three stages. The cyclic strain can be divided into cumulative irreversible strain and reversible strain. The magnitude of the reversible strain was approximately linear with the amplitude of cyclic stress[7]. Based on the triaxial creep test of Tianjin Binhai soft soil, Lei et al. used microscopic quantitative techniques to compare the microscopic structures of soil samples under static and dynamic load creep conditions, respectively, and elucidated the accelerated creep mechanism from the microscopic point of view. Their results showed that under cyclic loading, the strain changed slowly during the dynamic loading stage; however, after the dynamic loading ended and the stable stage was entered, the strain increased abruptly and finally tended to stabilize. Under different vibration frequencies and dynamic stress ratios, the specimens were subjected to different load levels, and there existed a critical safety load, beyond which the specimens would experience a creep failure phenomenon. The vibration load increased the degree of creep and accelerated the creep rate of the soil. The accelerated creep of soil is the self-adjustment and reconstitution process of the internal structure of soil under dynamic loading[8-10].

In this study, a creep test of reconstituted Tianjin silty clay under cyclic loading was carried out. The creep properties and stage divisions as well as the characteristics of the reversible strain and the cumulative plastic strain of saturated soft clay under cyclic loading were analyzed, which providing guidance for engineering construction in coastal areas.

2. Soils and testing methods

2.1. Soil samples
The test soil samples were extracted from the Tianjin Port area at a soil depth of 5 to 10 m and were silty clay. The extracted soil samples were disturbed. According to China’s Specification of Soil Test (SL237-1999), the samples were dried, ground, sieved and reconstituted to form saturated reconstituted specimens with a dry density of 1.25 g/cm³. Table 1 lists the basic physical properties of the soil samples.

| γ (g/cm³) | ω/ % | γd (g/cm³) | Sr/ % | e |
|-----------|------|------------|------|---|
| 1.8201    | 45.62| 1.2499     | 100  | 1.316 |

2.2. Test equipment and methods
A DCSS dynamic triaxial test system (GDS, United Kingdom) was used in the test. This equipment has two modules—namely, a dynamic single shear module and a dynamic triaxial module-enabling both axial vibration and horizontal dynamic simple shear. The axial vibration module was primarily selected in the test.

The specimen had a diameter of 39.1 mm and a height of 80 mm. Based on the in situ stress state of the soil sample, the cell pressure was determined to be 50 kPa. To simulate the load on the upper part of the foundation, the static deviatoric stress was selected as 0 kPa, 14 kPa and 28 kPa, respectively, and
the dynamic deviatoric stress was applied using the stepped loading method in the order of 5 kPa, 10 kPa, 15 kPa and 20 kPa. Due to the low permeability coefficient of saturated soft clay and thus low drainage under cyclic loading, the test was set as an undrained test during the cyclic loading process. A unidirectional stress of constant amplitude was used in the test to control the cyclic loading mode. The loading frequency was set as 0.5 Hz, the waveform was set as a sinusoidal wave, and the number of loadings at each step of cyclic loading was set as 10,000. The test scheme is shown in Table 2.

### Table 2. Creep test scheme

| Test | σ3/kPa | q_s/kPa | q_d/kPa     |
|------|--------|---------|-------------|
| D1   | 50     | 0       | 5-10-15-20  |
| D2   | 50     | 14      | 5-10-15-20  |
| D3   | 50     | 28      | 5-10-15-20  |

### 3. Test results and analysis

#### 3.1. Cyclic creep characteristics of saturated soft clay

To study the cyclic creep characteristics of saturated Tianjin silty clay, the creep test results under a cell pressure of 50 kPa, a static deviatoric stress of 0 kPa and a dynamic deviatoric stress of 5 kPa were analyzed as an example, as shown in Figure 1 and Figure 2. It can be seen in Figure 1 (a) that the creep curve at the initial stage of cyclic loading is approximately a sinusoidal waveform, and the curve gradually moves in the upper-right direction. Figure 1 (b) shows that the hysteresis curves continue to move toward the right and tend to be dense, indicating that a certain amount of plastic strain was accumulated in soil during each loading cycle while the accumulated amount gradually decreased; that is, the cumulative plastic strain gradually accumulated, but the rate of the cumulative plastic strain was attenuated rapidly. Figure 2 shows the characteristic creep curve at the late stage of cyclic loading. It can be seen in Figure 2 (a) that the cyclic creep curve exhibits a relatively regular sinusoidal waveform, indicating that the soil creep was essentially stable and the strain rate approached zero. Figure 2 (b) shows that the hysteresis curves no longer move to the right but coincide. In the whole loading process, the cyclic creep presents the attenuation-stabilization characteristics and successively goes through the stages of fast increase, rapid attenuation and stabilization, which is similar to the attenuation-stabilization characteristics of the static creep curve.

![Figure 1. Characteristic creep curve at the initial loading stage](image)
3.2. Creep stage division of saturated soft clay

It can be seen from the above analysis that in the axial strain-time curve of each cycle, there exists a maximum strain point $\varepsilon_p$ and a minimum strain point $\varepsilon_v$. The maximum strain points in different cycles are connected to obtain a peak creep curve, and the minimum strain points are connected to obtain a valley strain curve. The base point $\varepsilon_b$ of each cycle can be determined by

$$\varepsilon_b = \left( \varepsilon_p + \varepsilon_v \right) / 2$$

(1)

where $\varepsilon_p$ is the peak strain point, and $\varepsilon_v$ is the valley strain point, which are the maximum and minimum strain points of each cycle, respectively. These base points are connected with smooth curves to obtain the base creep curve.

The peak creep curve, base creep curve and valley creep curve are equidistant and approximately parallel. Define the variable $\varepsilon_a$ as the distance between the parallel lines; then

$$\varepsilon_a = \left( \varepsilon_p - \varepsilon_v \right) / 2$$

(2)

From Formulas (1) and (2), we have

$$\varepsilon_p = \varepsilon_b + \varepsilon_a$$

(3)

$$\varepsilon_v = \varepsilon_b - \varepsilon_a$$

(4)

Formulas (3) and (4) show that, during each cyclic loading process, the cyclic creep varies within a range that is based on the base creep $\varepsilon_b$ and has the variable $\varepsilon_a$ as the strain amplitude. The generation and recovery of $\varepsilon_a$ are an elastic reversible change process. Therefore, $\varepsilon_a$ is defined as the reversible strain.

Figure 3 shows the typical cyclic creep curve. It can be seen in the figure that each cyclic loading generated a certain amount of cumulative irreversible plastic strain. Therefore, when the soil is subjected to long-term cyclic loading, the point corresponding to the plastic strain generated in each cycle is connected to obtain the base creep curve of the soil sample. That is, the base creep curve reflects the plastic characteristics of the soil, which is in essence the cumulative plastic strain curve of the soil. Therefore, the cyclic creep of saturated silty soft clay is composed of two parts: the cumulative plastic strain $\varepsilon_b$ and the reversible strain $\varepsilon_a$, which represent the plastic and elastic characteristics, respectively.
Figure 3. The typical cyclic creep curve at the loading stage

3.3. Analysis of the reversible strain of saturated soft clay

Formula (2) is used to calculate the values of the reversible elastic strain of tests D1, D2 and D3 under different cyclic loads. The relationship between the reversible elastic strain and the cyclic dynamic stress is shown in Figure 4. As shown in the figure, the reversible strain of the soil sample is related to the stress level of the dynamic load. Within the range of load that does not cause the failure of the soil sample, the greater the magnitude is of the cyclic stress, the greater the generated reversible strain. During the cyclic creep test, there was a critical amplitude of the cyclic stress. When the amplitude exceeded this critical value, the cyclic creep of the soil sample increased sharply, the soil sample was destroyed instantaneously, and the corresponding elastic property of the soil deteriorated.

![Figure 4. Relationships between reversible elastic strain and cyclic deviatoric stress](image)

(a) D1 test  (b) D2 test  (c) D3 test

Figure 4. Relationships between reversible elastic strain and cyclic deviatoric stress

3.4. Analysis of cumulative plastic strain of saturated soft clay

Chen’s method was used to process the test data, and the resulting cumulative plastic strain curve of the soil is shown in Figure 5. Under the undrained condition, the cumulative plastic strain of the specimen
increased with increasing dynamic deviatoric stress. When the soil was in a compressive state—i.e., the static deviatoric stress $q_s$ was greater than the dynamic stress $q_d$—under the condition of the same dynamic deviatoric stress, the greater the static deviatoric stress, the greater the cumulative plastic strain. At the initial loading stage, with the joint action of dynamic and static deviatoric stresses, the cumulative plastic strain increased rapidly. Afterwards, the rate of cumulative plastic strain started to decline rapidly, and the cumulative strain entered an attenuation stage and eventually reached the stabilization stage, when the rate of cumulative plastic strain approached zero. Therefore, the creep curve shows attenuation-stabilization characteristics and can be divided into the fast increase stage, the attenuation stage and the stabilization stage.

![Figure 5. Relationships between cumulative plastic strain curve and cyclic number](image)

4. Conclusions

(1) The cyclic creep curve exhibits attenuation-stabilization characteristics and successively goes through stages of fast increase, rapid attenuation and stabilization, similar to the attenuation-stabilization characteristics of the static creep curve.

(2) The cyclic creep curve of saturated soft clay can be divided into three characteristic creep curves: the peak creep curve, the base creep curve and the valley creep curve. The cyclic creep of saturated silty soft clay is composed of two parts: cumulative plastic strain and reversible strain, which represent the plastic and elastic characteristics, respectively.

(3) The reversible strain of the soil sample is related to the stress level of the dynamic load. The greater the magnitude of the cyclic stress, the greater the reversible strain. At the initial loading stage, under the joint action of dynamic and static deviatoric stresses, the cumulative plastic strain increases rapidly. As the number of cycles increases, the cumulative plastic strain enters the attenuation stage and eventually reaches the stabilization stage.

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