Effect of the Principal Stress Direction on Cyclic Cumulative Deformation and Pore Pressure of Soft Clay

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Abstract

Permanent settlement of the subsoil induced by traffic load has been paid more and more attention recently. Predicting the traffic-load-induced permanent settlement correctly especially on saturated soft clay ground has been an important issue for the highway construction. For this propose, simplified methods based on empirical models for predicting the accumulative deformations of soft clays are usually preferred. Numerous experimental studies have been conducted by cyclic triaxial tests. However, little is known concerning the effects of principal stress direction, where the major principal stress direction is rotated away from the vertical by an angle due to undrained embankment loading. In this paper, a series of undrained cyclic tests with the hollow cylinder apparatus have been performed on Shanghai soft clay samples that involved different directions of the principal stress. In order to create explicit (empirical) models for predicting cyclic cumulative strain and pore water pressure, undrained static tests were also conducted under different directions of the principal stress. Test results show that the cumulative plastic strain and pore water pressure depend not only on the effective confining pressure, applied cyclic stress ratio and number of cycles, but also on the direction of principal stress. The improved explicit (empirical) models previously proposed to calculate the cumulative axial plastic strain and pore water pressure of saturated clay from the cyclic triaxial tests are further verified by the cyclic hollow cylinder tests under fixed directions of the principal stress. Such improved explicit (empirical) models will provide an effective approach to calculating the long-term settlement of highway embankment built on the soft ground caused by traffic load.

Keywords: Cyclic cumulative deformation and pore pressure, principal stress direction, soft clay, hollow cylinder apparatus

1 Introduction

The permanent settlement of the subsoil induced by traffic load is one of the key factors which control the design life and the maintenance cost of highway. To propose a cost-effective design, it is desirable to correctly predict the traffic-load-induced permanent settlement especially on saturated soft
clay ground. Miura et al. (1995) reported that one low embankment highway constructed on Ariake clay in Japan, the settlement of which had been come up to 1~2 m after 5 years operation. Similar situation has been occurred in China, for example, the subsidence, tracking and crack of the asphalt pavement of Shanghai outer ring highway have also been found due to the excessive deformation of the subsoil (Ling et al., 2002). These practices indicate that the deformation and differential settlement of the subsoil caused by traffic load will induce the crack of pavement and excessive deformation of road embankment, which will reduce the travelling comfort and increase the maintenance cost of highway.

Numerous experimental studies have been conducted on conventional triaxial loading tests (Sakai et al., 2003; Huang et al., 2006; Huang & Yao, 2012; Wichtmann et al., 2013; Guo et al., 2013). However, little is known concerning the effect of static embankment loading. Such an effect can be taken into consideration under either drained or undrained condition. Drained condition represents anisotropic “inclined” consolidation, where the major principal stress direction is rotated away from the vertical by an angle during consolidation due to embankment loading. Undrained consideration on the rotation of principal stress direction is supported if the consolidation is very slow or a conservative prediction of traffic-load-induced cumulative deformation is expected.

Setting up a constitutive model for calculating the cumulative plastic strain of saturated clay subjected to cyclic loading is the key work to permanent settlement analysis of soft subsoil induced by traffic load. Constitutive models for describing the accumulative deformation of soils under cyclic load can be divided into two types: implicit models and explicit (empirical) models. Typical implicit models include the bounding surface models, nested yield surface models and so on. Since the implicit model can only simulate the detailed process under each cyclic load, it is difficult to predict the traffic-load-induced permanent settlement by such a model due to a large number of cycles. As a result, the explicit models based on the experimental or measured data can be a more practical method to predict the traffic-load-induced permanent settlement.

The explicit (empirical) models mainly include the exponential model proposed by Monismith et al (1975), Li & Selig (1996) and Chai & Miura (2002). Huang et al (2006) and Huang & Yao (2012) proposed a new explicit (empirical) model different from the conventional explicit (empirical) model whose parameters were difficult to determined and uncertain in physical meaning. Hence, it is suitable for predicting the permanent settlement subjected to large number cyclic loading.

However, these explicit models mentioned above were developed from the results of conventional triaxial tests. It obviously cannot reflect the effect of the principal stress direction in soil due to the embankment loading. If an accumulative strain model for soil which is able to describe the effect of different principal stress directions can be developed from the experimental results under cyclic loading under a fixed principal stress direction, such a model will be more reasonable for predicting the permanent settlement under cyclic loading.

Optimization exists in the experiments with the conventional cyclic triaxial device for simulating the rotation of principal stress direction. Dynamic hollow cylinder apparatus will be an ideal choice to investigate the effect of the principal stress direction in present due to its ability to simulate various loading condition in complex stress paths.

In this paper, a series of tests with the dynamic hollow cylinder apparatus was performed on the saturated Shanghai soft clay and the development of cyclic accumulative deformation in the saturated soft clay is discussed under fixed principal stress directions. Meanwhile, the rationality of the explicit (empirical) model proposed by the authors is verified accounting for the effect of the principal stress direction on the undrained shear strength. It is more effective to predict the permanent settlement with the explicit (empirical) model for saturated soft clay which is capable of simulating the cyclic loading condition under various principal stress directions.
2 Static and Cyclic Hollow Cylinder Tests under Fixed Inclination of Principal Stress

Block samples were taken from the Shanghai soft clay in a construction site on the Caoxi road in Shanghai at a depth of 10-12 m. The physical indexes of the sample are as follows: natural water content \( w = 47.7\% \), unit weight \( \gamma = 17.8 \text{kN/m}^3 \), specific gravity \( G_s = 2.67 \), initial void ratio \( e_0 = 1.40 \), plastic index \( I_p = 23.5 \).

![Fig. 1: Dynamic hollow cylinder shear apparatus](image1)

![Fig. 2: Observed undrained shear strengths against the angle of rotating principal stress](image2)

The GDS dynamic hollow cylinder apparatus (HCA) was used in this study, as shown in Fig. 1. Firstly, the static undrained shear tests under isotropic consolidated conditions by HCA were performed on the Shanghai soft clay under fixed directions of the principal stress. In this test, the isotropic consolidated pressure \( p_0 \) was 100kPa, the coefficient of intermediate principal stress \( b \) was 0.5 and the rotational angle of principal stress axes \( \beta \) was fixed at 0º, 15º, 30º, 45º and 60º, respectively. Fig. 2 shows the variation of normalized undrained shear strength (peak stress ratio) with the principal stress direction, and the tests for \( \beta = 0º \) were also conducted with HCA. The test results shown Fig. 3 indicate that the peak stress ratio decreases as the angle between the major principal stress direction and the vertical \( \beta \) increases from 0º to 45º, increases as \( \beta \) increases from 45º to 60º, and has the minimum value at \( \beta = 45º \).

Next, the cyclic triaxial tests under isotropic consolidation conditions and the cyclic loading tests by HCA with fixed principal stress directions were performed on the Shanghai soft clay. The number of load cycles was 6000, and the load frequency was 1 Hz. The test program is shown in Table 1, where the tests at \( \beta = 0º \) correspond to the cyclic loading triaxial tests.

| \( p_0 \) (kPa) | \( q_d \) (kPa) | \( \beta \) (º) |
|-----------------|----------------|-----------------|
| 100             |                |                 |
| 10              | 0              | 15, 30, 45      |
| 15              |                |                 |
| 20              | 0              | 30              |
| 150             |                |                 |
| 15              | 0              | 30              |
| 30              |                |                 |

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Table 1: Cyclic HCA and triaxial test program

In the normally consolidated undrained dynamic hollow cylinder tests, the cyclic accumulative strain can be expressed as \( \varepsilon_i = (2\varepsilon_{ij} \varepsilon_{ij} / 3)^{1/2} \), where \( \varepsilon_{ij} = \varepsilon_{ij} - \delta_{ij} \varepsilon_{kk} / 3 \); and the dynamic stress \( \eta_d \) is defined as \( q_d / p_0 \).

Accumulative strain and pore water pressure of the saturated soft clay under cyclic loading are controlled by the direction of major principal stress, dynamic stress ratio and consolidation pressure, etc.. As shown in Figs. 3(a) and 3(b), the cyclic accumulative strain increases as the angle of principal stress direction \( \beta \) increases from 0º to 45º at the same consolidation pressure and dynamic stress ratio. It increases with an increase of the confining pressure at the same principal stress direction and dynamic stress ratio, as shown in Fig. 3(c), and it also increases with an increase of the dynamic stress ratio at the same confining pressure and the same principal stress direction, as shown in Fig. 3(d).

![Graphs showing the relationship between cyclic accumulative strain and number of cycles](image-url)

**Fig. 3:** Relationship between axial cycle cumulative strain and number of cycles
Figs. 4(a), 4(b) and 4(c) show cyclic cumulative pore water curves varying with the number of cycles. It can be found from the curves that the development of cyclic cumulative pore water pressure has a similar trend as that of the cyclic cumulative strain considering the effect of the angle of major principal stress, dynamics stress ratio and confining pressure.

3 Explicit Model for Predicting Cyclic Cumulative Strain and Pore Water Pressure

3.1 An Explicit Model for Predicting Cyclic Cumulative Strain

Based on the relationship between the dynamic deviatoric stress level and the first-cycle cumulative strain, an explicit equation for predicting the cyclic cumulative strain was proposed by Huang & Yao (2012). It can expressed as

$$\varepsilon^c = a D_d^a \left( \frac{p_0}{p_a} \right)^n N^b$$

where $p_0$ is the confining pressure, $p_a=101kPa$, $D_d$ is the dynamic deviatoric stress level, and $D_d= q_d/q_{ult}$. The values of $a$ and $n$ reflect the effect of the dynamic deviatoric stress level on the first-cycle cumulative strain normalized to the confining pressure, which are obtained by fitting the curve between the first-cycle cumulative strain normalized to confining pressure. Parameter $c$ reflects the
influence of confining pressure on the first-cycle cumulative strain, and parameter $b$ reflects the effect of number of cycles on the cyclic cumulative strain.

In order to consider the effect of the principal stress direction on the cyclic cumulative strain, $q_{ult}$ is set as the ultimate shear strength or the failure shear strength of the saturated soft clay from the HCA tests at fixed principal stress directions.

In a certain range of confining pressure, the first-cycle cumulative strain $\varepsilon^{p}_{1}$ is an exponential function of the confining pressure under cyclic loading at the same angle of principal stress direction and the same dynamic stress ratio. Fig. 5 reveals the relationship between the dynamic deviatoric stress level and the value of $a$ ($\varepsilon^{p}_{1}$ normalized by $(p_{0}/p_{a})^{1/2}$) for various angles of principal stress direction. It has been demonstrated that the effect of the principal stress direction on the cyclic cumulative strain can be considered with the undrained shear strength accounting for the rotation of the principal stress direction.

3.2 An Explicit Model for Predicting Cyclic Cumulative Pore Water Pressure

Similar to the explicit cumulative strain model described above, a cyclic cumulative pore water pressure model was also proposed by Huang & Yao (2012) based on the concept of the dynamic deviatoric stress level $D_{d}$. It can be written as:

$$\frac{u}{p_{a}} = a_{u}(D_{d})^{c} \left(\frac{p_{0}}{p_{a}}\right)^{c} N^{n_{u}}. \quad (2)$$

where the values of $a_{u}$ and $n_{u}$ reflect the influence of the dynamic deviatoric stress level on the first-cycle cumulative pore water pressure normalized by the confining pressure, which are obtained by fitting the curve between the first-cycle cumulative pore water pressure $\mu_{1}$ normalized to confining pressure; parameter $c$ reflects the effect of confining pressure on the first-cycle cumulative pore water pressure, and parameter $b_{u}$ reflects the effect of number of cycles on the cyclic cumulative strain.

Fig. 6 shows the relationship between the dynamic deviatoric stress level and the value of $\mu_{1}/p_{a}$ normalized by $(p_{0}/p_{a})^{1/2}$ for various angles of principal stress direction. Good correlation has been achieved.

![Fig. 5: Relationship between $A$ and $D_{d}$](image1)

![Fig. 6: Relationship between $(\mu_{1}/p_{a})/(p_{0}/p_{a})^{1/2}$ and $D_{d}$](image2)
3.3 Model Verification

Model parameters of the cyclic cumulative strain model and the corresponding pore water pressure model considering different directions of the principal stress are shown in Table 2. It can be seen from Fig. 7 that the simulated results by the proposed cumulative strain model are close to the experimental results. It indicates that the model can predict the cyclic cumulative strain of saturated soft clay under cyclic loading with different angles of the principal stress direction. Fig. 8 compares the experimental accumulative pore water pressures and the simulated ones under cyclic loading with fixed angles of principal stress direction. It also indicates that the model can predict the cyclic cumulative pore water pressure of saturated soft clay under cyclic loading with different angles of principal stress direction.

|   |   |   |   |
|---|---|---|---|
| a | 0.076 | 0.0385 |
| n | 1.408 | 1.37 |
| c | 0.5 | 0.5 |
| b | 0.408 | 0.32 |

Table 2: Model parameters

Fig. 7: Relationship between cyclic cumulative strain and number of cycles
4 Conclusions

In this paper, a series of static and cyclic consolidated undrained tests were performed on the Shanghai saturated soft clay with constant principal stress direction. The variation of cyclic accumulative strain and pore water pressure were investigated, and the explicit (empirical) models for their predictions are developed. The simulated results show that the explicit (empirical) model can describe the effect of the rotation of initial principal stress direction. The major parameters of this model have definite physical meaning. Since a few parameters are used and easy to be determined, this model can be more convenient to predict the permanent foundation settlement subjected to long-term cyclic loading.

The magnitude and direction of the principal stress of soil elements in the subgrade will change continuously under traffic load. Therefore, it is necessary to further improve the tests in continuous ranges of magnitude and directions of the principal stress, and develop the model which can describe the more complex stress path closer to the practical situation.

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![Graph](image)

**Fig. 8:** Relationship between cumulative pore pressure and number of cyclic loading

(a) $p_0 = 100\text{kPa}, \eta_d = 0.1$
(b) $\beta = 30^\circ, \eta_d = 0.1$
(c) $p_0 = 100\text{kPa}, \beta = 30^\circ$
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