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The deformation characteristics of saturated clay in three-dimensional cyclic stress state

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Abstract: The dynamic stress field induced by moving loads is three-dimensional, involving the cyclic variation of major, intermediate and minor principal stresses, while so far very limited laboratory studies have been undertaken on the one-way deformation behavior of saturated clays in three-dimensional stress state. In this study, an advanced true triaxial apparatus, which can apply cyclic major and intermediate principal stresses simultaneously, is employed to carry out a total of 65 one-way cyclic tests on both normally and overconsolidated clays. Four values of overconsolidation ratio (OCR), five values of b_{cyc} , which is termed the coefficient of cyclic intermediate principal stress, and a wide range of cyclic stress ratio (CSR) are tested. Emphasis is put on the effects of b_{cyc} and OCR on the characteristics of permanent major and intermediate principal strains. Test results show that the increase of b_{cyc} significantly reduces the accumulation of major principal strain, and linear relationships are observed between the permanent major principal strain and b_{cyc} for test data with the same CSR, OCR and cycle number. A critical value of $b_{cyc} \approx 0.5$, at which the permanent intermediate principal strain changes from tension to compression, is observed for the remolded clay. Furthermore, an empirical model is proposed, allowing the long-term deformation of saturated clays to be predicted in three-dimensional cyclic stress state.

Key words: true triaxial tests, clays, intermediate principal stress, stress path, traffic loading

57 Introduction

58 The deformation behavior of soils under one-way cyclic loadings is of great importance in many
 59 engineering problems, such as the prediction of soil settlements under moving loads. Specifically, it has
 60 been recognized widely that the moving loads induced by passing vehicles lead to an important component
 61 of the total pavement settlement especially in soft clay areas (Chai and Miura 2002; Guo et al. 2013).

62 Laboratory tests, such as the cyclic axisymmetric triaxial and HCA (hollow cylinder apparatus) tests,
 63 have been extensively employed to study the one-way deformation characteristics of saturated clays. In the
 64 axisymmetric triaxial tests with a constant confining pressure (CCP tests), the cyclic axial stress follows a
 65 waveform which is purely compressive without reversal, such that the axial stress remains the major
 66 principal stress, to simulate the traffic-induced one-way vertical normal stress (termed $\Delta\sigma_{11}$ herein) in
 67 one-dimensional stress state (e.g., Hyde and Brown 1976; Hyodo et al. 1992; Hyde et al. 1993; Moses and
 68 Rao 2003; Guo et al. 2013). In the axisymmetric triaxial tests with a variable confining pressure (VCP tests),
 69 a combination of one-way cyclic axial stress and confining pressure is applied in phase, to simulate the
 70 coupling of traffic-induced vertical ($\Delta\sigma_{11}$) and horizontal normal stresses in both directions (termed $\Delta\sigma_{22}$ and
 71 $\Delta\sigma_{33}$, respectively). The amplitudes of the two cyclic horizontal normal stresses ($\Delta\sigma_{22}$ and $\Delta\sigma_{33}$) are
 72 simplified to be equal and then represented by the same cyclic confining pressure (e.g., Rondón et al. 2009;
 73 Cai et al. 2013; Sun et al. 2015a; Sun et al. 2015b; Gu et al. 2016). In the HCA tests, the cyclic axial and
 74 shear stresses are applied simultaneously, to mimic the coupling of traffic-induced vertical ($\Delta\sigma_{11}$) and shear
 75 stresses (termed $\Delta\sigma_{12}$) (e.g., Cai et al. 2017; Wu et al. 2017; Guo et al. 2018). Compared to the CCP tests,
 76 the cyclic stress paths in VCP and HCA tests can be described in the two-dimensional $p - q$ (mean principal
 77 stress - deviatoric stress) and $\tau_{z\theta} - (\sigma_z - \sigma_\theta)$ [shear stress - (axial stress-lateral stress)] planes, respectively. The
 78 studies based on these two-dimensional tests indicated that the stress component (the cyclic confining
 79 pressure in VCP tests or the cyclic shear stress in HCA tests) additional to the cyclic axial stress made

significant effects on the deformation behavior of saturated clays. For example, Cai et al. (2013), Sun et al. (2015a,b) and Gu et al. (2016) compared the deformation of saturated clays between CCP and VCP tests, and concluded that the cyclic confining pressure promoted the accumulation of permanent axial strain greatly for both normally and overconsolidated clays. Cai et al. (2017) and Guo et al. (2018) found that the cyclic rotation of principal stress in HCA tests, which was induced by the coupling of cyclic axial and shear stresses, increased the development of permanent strains.

Nevertheless, the three traffic-induced cyclic normal stresses applied on subgrade soils, i.e., the vertical normal stress ($\Delta\sigma_{11}$), horizontal normal stress parallel to the road direction ($\Delta\sigma_{22}$) and horizontal normal stress perpendicular to the road direction ($\Delta\sigma_{33}$), usually vibrate with different magnitudes in phase. For example, based on a finite element calculation, Bian et al. (2008) found that all of $\Delta\sigma_{11}$, $\Delta\sigma_{12}$ and $\Delta\sigma_{33}$ are one-way compressive stresses and the ratios of $\Delta\sigma_{22}$ and $\Delta\sigma_{33}$ to $\Delta\sigma_{11}$ are 36.0% and 17.3%, and 22.2% and 0% for the soils beneath 0 and 3 m embankments, respectively. Powrie et al. (2007) performed a three-dimensional finite element analyses and calculated that the ratios of $\Delta\sigma_{22}$ and $\Delta\sigma_{33}$ to $\Delta\sigma_{11}$ are 65.6% and 39.3%, and 40.6% and 0% for the soils beneath 1.19 and 4.04 m embankments, respectively. It is observed that $\Delta\sigma_{22}$ is relatively large compared to $\Delta\sigma_{11}$, while $\Delta\sigma_{33}$ can almost be ignored especially when the soil depth reaches a certain extent. The differences among the three traffic-induced normal stresses imply that the VCP tests may be inappropriate to simulate the cyclic normal stresses under passing wheels, while the true triaxial apparatus, which enables the simultaneous application of cyclic major and intermediate principal stresses, may be a good candidate to investigate the traffic-induced deformation behavior of subgrade soils.

True triaxial tests have been employed widely to study the mechanical behavior of soils in three-dimensional stress state, such as those in slopes, foundations, embankments and in excavations (e.g., Prashant and Penumadu 2004; Anantanasakul et al. 2012). The initial stress state of soils in situ may be

three-dimensional rather than axisymmetric, i.e., the magnitudes of the three initial principal stresses applied on soil elements may differ from each other (Prashant and Penumadu 2005; Xiao et al. 2014). Moreover, many researches (e.g., Lade and Musante 1978; Nakai and Matsuoka 1986; Prashant and Penumadu 2004; Anantanasakul et al. 2012; Yang et al. 2018) indicated that the three-dimensional triaxial monotonic shearing was more appropriate to simulate the real loading condition in some cases, compared to the axisymmetric triaxial tests. Most of the previous studies emphasized the effects of intermediate principal stress (in terms of the coefficient of intermediate principal stress, b , or Lode angle, θ) on the shear characteristics of saturated soils (Kirkgard and Lade 1993; Callisto and Calabresi 1998; Callisto et al. 2002; Prashant and Penumadu 2005; Anantanasakul et al. 2012; Ye et al. 2014). However, few researches have considered the traffic-induced three-dimensional cyclic normal stresses, and very limited studies have been reported on the one-way deformation characteristics of saturated clays in three-dimensional stress state. Gu et al. (2018) considered the $\Delta\sigma_{22}$ induced by traffic loading and performed a series of cyclic true triaxial tests on a saturated clay. It was found that the cyclic intermediate principal stress made significant effects on the deformation characteristics. However, they only tested samples with one overconsolidation ratio (OCR) within a relatively narrow range of cyclic stress magnitude, and no prediction models of permanent strains were proposed.

In this study, a number of 65 one-way cyclic true triaxial tests were performed on a remolded saturated clay, based on an advanced true triaxial apparatus which enables the simultaneous application of cyclic major and intermediate principal stresses. Four values of overconsolidation ratio (OCR) were tested considering the varying OCR of subgrade soils along with the increasing depth. Five values of b_{cyc} , which is termed the coefficient of cyclic intermediate principal stress, were employed to represent the coupling of cyclic major and intermediate principal stresses. Emphases were placed on the effects of b_{cyc} and OCR on the permanent deformation characteristics, in terms of both major and intermediate principal strains.

Test Materials, Test Apparatus, Samples Preparation and Test Program

A remolded clay was selected as the experimental material to ensure the homogeneity of samples. The original clay was obtained from 3-4 meters beneath the ground surface, from a site in Wenzhou city. Its primary index properties are: specific gravity $G_s=2.63$, plastic limit $w_p=38\%$ and plasticity index $I_p=40$. According to the USCS classification method (ASTM D 2487-83), the clay is classified as CH (clay of high plasticity). A standard sample preparation procedure based on a large consolidation vessel was employed to guarantee the consistency of the sample quality (see Cai et al. 2018 for details).

An advanced true triaxial device, which was designed and manufactured by GDS Instruments Ltd., was used. It applies the confining pressure by water pressure, which is further provided by compressed air. The cyclic vertical stress ($\Delta\sigma_1$) and horizontal stress ($\Delta\sigma_2$) are provided by two horizontal metal plates with length=75mm and width=75mm and two vertical metal plates with width=75mm and height=140mm, respectively. Every metal plate is driven by a high-precision servo motor.

In the tests, the cyclic major and intermediate principal stresses (σ_1 and σ_2) were applied in phase and in a continuous haversine mode at amplitudes of σ_1^{ampl} and σ_2^{ampl} respectively, while the minor principal stress (σ_3) was kept constant (i.e., $\sigma_3^{ampl}=0$). A parameter termed the coefficient of cyclic intermediate principal stress, b_{cyc} , is employed herein following the definition of traditional intermediate principal stress parameter, b :

$$b_{cyc} = \frac{\sigma_2^{ampl} - \sigma_3^{ampl}}{\sigma_1^{ampl} - \sigma_3^{ampl}} = \frac{\sigma_2^{ampl}}{\sigma_1^{ampl}} \quad (1)$$

The sketch of the applied stress paths in σ_1 - σ_2 plane is presented in Fig. 1, in which the slopes of the stress paths represent the b_{cyc} values. As observed, both the cyclic major and intermediate principal stresses are purely compressive and the direction of major principal stress axis stays constant.

The test program is given in Table 1, involving 65 tests with different combinations of CSR, b_{cyc} and

OCR. Four OCR values of 1, 2, 4, and 8 were employed, considering both normally and overconsolidated clays. Five b_{cyc} values of 0, 0.2, 0.4, 0.6, 0.8 were tested to study the different combinations of cyclic major and intermediate principal stresses. Overconsolidation ratio (OCR) is the ratio of the preconsolidation mean effective principal stress, p'_{OC} , to the current mean effective principal stress, p'_0 , i.e., $OCR = p'_{OC} / p'_0$. The cyclic stress ratio (CSR) is defined as the ratio between the amplitude of cyclic shear stress, q^{ampl} , and the double undrained shear strength, S_u , i.e., $CSR = q^{ampl} / 2S_u$. The preliminary true triaxial compression tests indicated that S_u for samples of OCR=1, 2, 4 and 8 under $p'_0=60$ kPa are 44.6 kPa, 73.7 kPa, 108.5 kPa, 171.2 kPa, respectively. q^{ampl} is obtained by:

$$q^{ampl} = \frac{\sqrt{2}}{2} \sqrt{(\sigma_1^{ampl} - \sigma_2^{ampl})^2 + (\sigma_1^{ampl} - \sigma_3^{ampl})^2 + (\sigma_2^{ampl} - \sigma_3^{ampl})^2} \quad (2)$$

The values of permanent major and intermediate principal strains, ε_1^p and ε_2^p , at the end of tests are also given in Table 1.

The size of the cuboid samples was length×width×height=75mm×75mm×155mm. All samples were firstly saturated under a back pressure of 300 kPa with an effective confining pressure of 20 kPa, until B values larger than 0.97 were achieved. For the overconsolidated samples, the specimen was initially consolidated under an effective confining pressure of (60×OCR) kPa, following which the effective stress was reduced to $p'_0=60$ kPa. The drainage (or swelling) rate of pore water, whose value was below 1 mm³/min, was used as the criterion of consolidation completion. All the samples were consolidated isotropically.

After the consolidation, the cyclic major and intermediate principal stresses were applied in phase on the specimens in undrained conditions. The cycle numbers for all tests were 10,000 except for the samples which failed before $N=10,000$. The slow loading frequency of 0.1 Hz was selected to ensure the quality of cyclic stress control and the even distribution of pore water pressures.

Test Results and Discussion

The cyclic evolution of strains

The typical cyclic evolution of major principal strain (ε_1) and intermediate principal strain (ε_2) with time are presented in Figs. 2(a) and (b), respectively. The maximum major and intermediate principal strains, $\varepsilon_1^{\max}$ and $\varepsilon_2^{\max}$, permanent strains ε_1^p and ε_2^p , resilient strains ε_1^r and ε_2^r are marked in Fig. 2. In general, the development of both ε_1 and ε_2 shows a nonlinear behavior, in which the development rates tend to decrease with the increase of time.

The cyclic evolution of permanent shear strain (ε_q^p), major principal strain (ε_1^p), intermediate principal strain (ε_2^p) and minor principal strain (ε_3^p) with cycle number, N , for typical tests of OCR=1, 2 and 4 are illustrated in Figs. 3, 4 and 5, respectively. ε_1^p and ε_2^p were measured and recorded by the apparatus, while ε_q^p and ε_3^p were calculated by the equations of $\varepsilon_q^p = (\sqrt{2}/3)[(\varepsilon_1^p - \varepsilon_2^p)^2 + (\varepsilon_2^p - \varepsilon_3^p)^2 + (\varepsilon_3^p - \varepsilon_1^p)^2]^{0.5}$ and $\varepsilon_3^p = -\varepsilon_1^p - \varepsilon_2^p$, respectively. It should be noted that for the tests of $b_{cyc} = 0$, ε_2^p could not be measured because the displacement sensors connected to the metal plates were away from the samples, then $\varepsilon_2^p = \varepsilon_3^p = -0.5\varepsilon_1^p$.

For the tests of $b_{cyc} = 0$ [Fig. 3(a), Fig. 4(a) and Fig. 5(a)], ε_q^p equals to ε_1^p and they are compression strains, while $\varepsilon_2^p = \varepsilon_3^p$ and they are negative all through the tests, indicating that the specimens are tensed in the directions of σ_2 and σ_3 . When b_{cyc} increases to 0.2 [Fig. 4(b)], ε_2^p is still tension strain but becomes larger than ε_3^p . For the tests of $b_{cyc}=0.8$ [Fig. 3(c), Fig. 4(e) and Fig. 5(c)], all of ε_q^p , ε_1^p and ε_2^p are positive, while ε_3^p is negative. Moreover, it appears that $\varepsilon_q^p > \varepsilon_2^p > \varepsilon_1^p$. When b_{cyc} decreases to 0.6 [Fig. 4(d)], ε_2^p is still positive but becomes lower than ε_1^p . For the tests of $b_{cyc}=0.4$ [Fig. 3(b), Fig. 4(c) and Fig. 5(b)], ε_q^p and ε_1^p are compression strains and ε_q^p is slightly larger than ε_1^p . ε_3^p is tension strain while ε_2^p shows a very different behavior, which almost stabilizes around zero all through the tests.

In general, ε_q^p and ε_1^p for all the tests are compression strains while ε_3^p is tension strain. ε_q^p and ε_1^p develop quickly at the beginning and then accumulate at decreasing rates until the end of tests. For the

tests with lower CSR values (e.g., when $CSR < 0.38$), both the ε_q^p and ε_1^p tend to reach steady values with the increase of cycle number. The trend of ε_3^p is similar to ε_q^p and ε_1^p except that it is negative. The development behavior of ε_2 is very complex. When $b_{cyc}=0$ and 0.2, ε_2 is negative and tends to decrease with the increase of cycle number. When $b_{cyc}=0.6$ and 0.8, ε_2 is positive and shows an increasing tendency. When $b_{cyc}=0.4$, ε_2 is around zero and shows no obvious changes all through the tests, regardless of OCR and CSR.

As the volume of samples can be considered constant in undrained conditions, the changes of the relative magnitude between cyclic intermediate and major principal stresses lead to the changes of the relative relationships among the four strains of ε_q^p , ε_1^p , ε_2^p and ε_3^p , in terms of direction and value.

To show the influences of b_{cyc} on the coupling of ε_1^p and ε_2^p more clearly, the comparison of $\varepsilon_1^p - \varepsilon_2^p$ curves among tests with the same OCR and CSR but different b_{cyc} values is presented in Fig. 6. As a reference, the applied stress paths in $\sigma_1 - \sigma_2$ plane are also plotted in dotted lines. The slopes of the $\varepsilon_1^p - \varepsilon_2^p$ curves signify the directions of strain paths. In general, the strain paths tend to rotate anticlockwise as b_{cyc} increases, independent of CSR and OCR. When $b_{cyc}=0$, the strain paths are below the X-axis, and go downward linearly with the increase of strains, due to the reason that ε_2^p is calculated by the equation of $\varepsilon_2^p = -0.5\varepsilon_1^p$. When $b_{cyc}=0.8$, the $\varepsilon_1^p - \varepsilon_2^p$ curves are above the X-axis and go upward gradually. However, for the tests of $b_{cyc}=0.4$, almost all the strain paths vibrate around the X-axis.

The comparison between the stress and strain paths of the same test shows that, when $b_{cyc}=0$ and 0.4, the strain path is below the stress path and the phase difference between the two paths is great. However, when b_{cyc} increases to 0.8, the strain path is generally above the stress path and the phase difference becomes smaller. It is speculated that the complex behavior of permanent intermediate principal strain is the main reason leading to the changes of phase differences between the strain and stress paths.

Permanent major principal strain

The comparison of permanent major principal strain, ε_1^p , among tests with the same CSR and OCR but

different b_{cyc} values is shown in Fig. 7. In general, the increase of b_{cyc} reduces the accumulation of ε_1^p remarkably, regardless of OCR and CSR, indicating that the conventional triaxial tests with only a single cyclic axial stress may overestimate the traffic-induced settlement of subgrade soils in undrained condition. Taking two groups of tests with CSR=0.217 and OCR=1 [Fig. 7(a)] and CSR=0.245 and OCR=4 [Fig. 7(e)] as examples, ε_1^p values at $N=10000$ for $b_{cyc}=0.8$ are only 32.3% and 48.8% their counterparts for $b_{cyc}=0$, respectively. This is mainly because that the larger amplitude of cyclic intermediate principal stress restricts the development of major principal strain.

To quantify the effects of b_{cyc} on the accumulation of ε_1^p , for the tests with the same CSR and OCR but different b_{cyc} , ε_1^p at specific cycle numbers is plotted versus the corresponding b_{cyc} . Fig. 8 presents the comparison of ε_1^p - b_{cyc} relationships among five cycle numbers (i.e., $N=500, 1500, 2500, 5000$ and 10000) for six typical tests. It can be seen that ε_1^p at the same cycle number decreases almost linearly with the increase of b_{cyc} , regardless of CSR, OCR and N . Similar linear relationships are also observed for other tests especially when CSR is low. The fitted lines can be expressed as:

$$\varepsilon_1^p(\%) = A \times b_{cyc} + B \quad (3)$$

where A is the slope of the fitting line, i.e., the increment of ε_1^p induced by one unit increment in b_{cyc} value at a specific cycle number. B is the intercept of the fitting line and approximately equals to the value of ε_1^p when $b_{cyc}=0$. All the A and B values are also marked in the figure.

As observed in Fig. 8, the increase of cycle number reduces the values of A , suggesting that the accumulation of cycle number promotes the reduction of ε_1^p induced by the cyclic intermediate principal stress. Taking Fig. 8(b) as an example, the slopes (A values) are -0.376, -0.470 and -0.578% for the fitted lines of $N=2500, 5000$ and 10000 , respectively, i.e., one unit increment in the b_{cyc} value leads to an increment of -0.376, -0.470 and -0.578% in ε_1^p . Considering that the maximum value of ε_1^p in Fig. 8 (b) is only 0.803%, the reduction is great.

Fig. 9 further shows the relationships of A and B in Eq. 3 against the cycle number, N . In general, A is negative while B is positive. A decreases nonlinearly with the increase of N and tends to stabilize, and the trend of B is similar to that of A except that it grows up with N . The A - N and B - N patterns show that the reduction of ε_1^p induced by b_{cyc} may stabilize when the cycle number becomes large enough, especially for tests of lower CSR values.

To show the trends of A and B versus N more clearly, the A - N and B - N curves are re-plotted in the semi-log space in Fig. 10. It appears that all the curves present linear relationships. The fitted lines (dashed lines) are also plotted in the figure. The maximum value of X-axis (N) is set as 1,000,000, to show the predicted values of A and B after $N=10,000$. The slopes of the fitted lines are marked in the figure, which show a decreasing or increasing trend with the increase of CSR for Fig. 10(a) or (b), respectively.

Although Fig. 10 gives the quantitative relationships of A and B versus N , however, the effects of OCR and CSR on the A and B values are still unknown. In particular, the fitted values of A and B at the last cycle number ($N=10,000$) and the predicted values of A and B at $N=100,000$ are further employed to plot against CSR in Figs. 11(a) and (b), respectively. Both figures show that the increase of CSR reduces A and increases B considerably, indicating that the increase of CSR promotes the reduction of ε_1^p induced by b_{cyc} . For instance [Fig. 11(a)], when $N=10,000$, the ratios of A and B between the tests of CSR=0.417 and 0.290 at OCR=2 reach 26.7 and 12.1, respectively. Moreover, both the A -CSR and B -CSR trends can be fitted well by specific equations. It appears that the values of A and B may be related to cycle number and CSR, but slightly influenced by OCR. The general form of the equations can be expressed as follows:

$$A = D_A + E_A \times CSR^{F_A} \quad (4)$$

$$B = D_B + E_B \times CSR^{F_B} \quad (5)$$

Eq. 3 constitutes a simple way to calculate the permanent major principal strain at a specific cycle number, while Eqs. 4 and 5 present the relationships of A and B with CSR. Substituting Eqs. 4 and 5 into Eq.

3, Eq. 6 is obtained, which can be used to calculate the permanent strain at a specific cycle number:

$$\varepsilon_1^P (\%) = (D_A + E_A \times CSR^{F_A})b_{cyc} + (D_B + E_B \times CSR^{F_B}) \quad (6)$$

For the cycle numbers of $N=10,000$ and $100,000$, Eq. 6 is obtained as:

$$\varepsilon_1^P (\%) = (-0.166 - 102233 \times CSR^{11.453})b_{cyc} + (0.281 + 72319 \times CSR^{11.057}), \quad N=10,000 \quad (7)$$

$$\varepsilon_1^P (\%) = (-0.3635 - 1.331 \times 10^8 \times CSR^{18.092})b_{cyc} + (0.5219 + 1.720 \times 10^8 \times CSR^{18.413}), \quad N=100,000 \quad (8)$$

In order to verify the ability of Eq. 6 to predict the permanent deformation, the predicted values of A and B at $N=50,000$, $100,000$, $250,000$, $500,000$ and $1,000,000$ are obtained based on Eqs. 4 and 5, respectively (see Table 3 for the calculated values at $N=50,000$, $250,000$ and $1000,000$). They are further used to calculate the permanent major principal strains by Eq. 6. The predicted results of ε_1^P are marked in dot in Figs. 12 (a), (b) and (c) for typical tests of OCR=1, 2 and 4, respectively.

Fig. 12 shows the accumulation of permanent major principal strain in the double-log space. As can be seen, the curves appear to be good lines, and the following expression, which has been verified by many researches such as Guo et al. (2013) and Sun et al. (2015), can be used to predict the permanent strain:

$$\log \varepsilon_1^P = \log \varepsilon_{1,N_f}^P + k \log \frac{N}{N_f} \quad (9)$$

where N_f is the reference cycle number when the relationship between $\log \varepsilon_1^P$ and $\log N$ starts to get linear; ε_{1,N_f}^P is the permanent axial strain at N_f . k is the slope of the fitting line.

In this study, N_f in Eq. 9 can be determined as 1,000. The fitted lines (dashed lines) based on Eq. 9 are plotted in Fig. 12. As observed, the predicted values of ε_1^P through Eq. 6 are generally close to those by Eq. 9, indicating that Eq. 6 proposed in this study has a good ability to predict the long-term deformation of saturated clays in three-dimensional stress state. Moreover, the predicted ε_1^P by Eq. 6 are basically lower than the corresponding ε_1^P based on Eq. 9, and the differences (see Table 3 for the calculated percentage difference at $N=50,000$, $250,000$ and $1000,000$) tend to increase with the accumulation of cycle number. It is

argued that Eq. 9 has a significant drawback of no convergence, which means that the predicted deformation will increase continuously and result in the failure to predict. Considering that the A and B values in Eq. 6 trend to stabilize with the increase of cycle number (Fig. 9), Eq. 6 may be more appropriate to predict the deformation especially when the cyclic application number of traffic loading becomes very large.

It should be noted the fitted values of k in Eq. 9 are also marked in Fig. 12, which are approximately in the range of 0.10 to 0.25 for the tests in this study. We find it almost impossible to establish a uniform relationship of k versus CSR, OCR and b_{cyc} .

Summarizing, although Eq. 6 is verified well in Fig. 12, however, it does not implicitly include the variable of cycle number, N . This is because that the values of A and B vary with N , then the parameters of D , E and F in Eqs. 4 and 5 are also changed. Nevertheless, Fig. 9 shows that both A and B tend to stabilize when the cycle number becomes large enough. This implies that if the stable (or ultimate) values of A and B are obtained, Eq. 6 can be used to predict the ultimate permanent strains under a certain combination of cyclic major and intermediate principal stresses. Since the long-term deformation behavior of subgrade soils is the main concern in road engineering, in which the traffic loading is characterized by a significantly large cycle number and relatively low amplitude, the above findings will therefore be helpful to depict the long-term traffic-induced settlement in three-dimensional stress state.

Permanent intermediate principal strain

Fig. 13 shows the effect of cyclic intermediate principal stress on the permanent intermediate principal strain, ε_2^p . As stated in the previous section, the development of intermediate principal strain can be discussed in three different categories of b_{cyc} . This can be further verified by Fig. 13. In general, when $b_{cyc}=0$, ε_2^p is tension strain, while it changes to compression strain when $b_{cyc}=0.8$. However, ε_2^p for $b_{cyc}=0.4$ is around zero.

It is speculated that there may exist a critical value of b_{cyc} at which ε_2^p changes from tension to

compression, regardless of CSR and OCR. To determine this critical value, ε_2^p at the last cycle ($N=10,000$) are plotted versus b_{cyc} , as shown in Figs. 14(a), (b) and (c) for OCR=1, 2 and 4, respectively. It can be seen that the ε_2^p - b_{cyc} curves approximately intersect at the same point, corresponding to the changes of ε_2^p from tension to compression strain. The b_{cyc} values at the intersection points are approximately 0.501, 0.505 and 0.514 for OCR=1, 2 and 4, respectively, which are almost the same. The values of ε_2^p corresponding to the above three critical b_{cyc} values are -0.020, 0.065 and 0.233%, respectively, which are close to zero. This finding not only determines the critical value of b_{cyc} as approximate 0.5 for the clay used in this study, but also proves that the critical value is independent on CSR and OCR. Moreover, this critical value of b_{cyc} is very close to that of b (0.5) determined by monotonic shearing (Prashant and Penumadu 2004), suggesting that the proposed parameter, b_{cyc} , is a suitable parameter in characterizing the coupling of cyclic major and intermediate principal stresses.

Conclusions

In this study, a total of 65 one-way cyclic tests were carried out on a remolded clay by an advanced true triaxial apparatus. Different combinations of OCR, b_{cyc} and CSR were tested, to investigate the deformation behavior in three-dimensional stress state. Based on the test results, the following conclusions can be given:

(1) The deformation characteristics of saturated clay in three-dimensional stress state, in terms of both major and intermediate principal strains, shows great relevance with the cyclic intermediate principal stress. The cyclic intermediate principal stress can not be neglected in the prediction of subgrade deformation under traffic loading.

(2) The increase of cyclic intermediate principal stress (in terms of b_{cyc}) reduces the development of permanent major principal strain remarkably, and the reduction is further promoted by increasing cycle number and CSR. Linear relationships are observed between the permanent major principal strain and b_{cyc} for test data with the same CSR, OCR and cycle number. The parameters of A and B in Eq. 3 are related to

both cycle number and CSR, but slightly influenced by OCR.

(3) An empirical model of Eq. 6 is proposed, allowing the long-term deformation of saturated clays to be predicted. The comparison of predicted values between Eqs. 6 and 9 imply that Eq. 6 has a good ability to predict the long-term deformation of saturated clays in three-dimensional stress state.

(4) The behavior of intermediate principal strain is strongly dependent on b_{cyc} . A critical value of $b_{cyc} \approx 0.5$, at which ε_2^p changes from tension to compression strain, is determined, regardless of CSR and OCR. When CSR is lower than the critical value ($b_{cyc} = 0$ and 0.2), the intermediate principal strain is of tension nature. By contrast, when CSR is larger than the critical value ($b_{cyc} = 0.6$ and 0.8), the intermediate principal strain is compression. Both the results of permanent major and intermediate strains imply that OCR may be a minor influencing factor in the one-way cyclic behavior of saturated clays.

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Notation

$A, B, D_A, E_A, F_A, D_B, E_B, F_B$ = fitting parameter;

b_{cyc} = coefficient of cyclic intermediate principal stress;

q^{ampl} = amplitude of cyclic shear stress;

s_u = undrained shear strength;

ε_1^p = permanent major principal strain;

ε_2^p = permanent intermediate principal strain;

- 353 ε_3^p = permanent minor principal strain;
- 354 ε_q^p = permanent shear strain;
- 355 σ_1^{ampl} = amplitude of cyclic major principal stress;
- 356 σ_2^{ampl} = amplitude of cyclic intermediate principal stress;
- 357 σ_3^{ampl} = amplitude of cyclic minor principal stress;
- 358 N_f = reference cycle number.

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Figures captions

Fig. 1. Schematic of the applied stress paths in this study

Fig. 2. Typical cyclic evolution of (a) major principal strain and (b) intermediate principal strain versus time

Fig. 3. The accumulation of permanent strains under OCR=1 and CSR=0.370 for tests: (a) $b_{cyc}=0$; (b) $b_{cyc}=0.4$ and (c) $b_{cyc}=0.8$

Fig. 4. The accumulation of permanent strains under OCR=2 and CSR=0.290 for tests: (a) $b_{cyc}=0$; (b) $b_{cyc}=0.2$; (c) $b_{cyc}=0.4$; (d) $b_{cyc}=0.6$ and (e) $b_{cyc}=0.8$

Fig. 5. The accumulation of permanent strains under OCR=4 and CSR=0.328 for tests: (a) $b_{cyc}=0$; (b) $b_{cyc}=0.4$ and (c) $b_{cyc}=0.8$

Fig. 6. Influence of the stress paths on the strain paths for tests: (a) OCR=1, CSR=0.269; (b) OCR=1, CSR=0.370; (c) OCR=4, CSR=0.371 and (d) OCR=4, CSR=0.423

Fig. 7. Effects of b_{cyc} on the permanent major principal strain

Fig. 8. Relationships of permanent major principal strains versus b_{cyc} for test data with the same CSR, OCR and N

Fig. 9. Effects of cycle number on the parameters of (a) A and (b) B in Eq. 3

Fig. 10. Prediction of the parameters of (a) A and (b) B in Eq. 3 in semi-log space

Fig. 11. Influences of CSR on the parameters A and B in Eq. 3 for: (a) $N=10,000$ and (b) $N=100,000$

Fig. 12. Comparison of predicted ε_1^p between Eqs. 6 and 9 for: (a) OCR=1, CSR=0.346; (b) OCR=2, CSR=0.328 and (c) OCR=4, CSR=0.328

Fig. 13. Effects of cyclic intermediate principal stress on the permanent intermediate strain

Fig. 14. Determination of the critical value of b_{cyc} : (a) OCR=1; (b) OCR=2; (c) OCR=4

Table 1. Summary of the true triaxial tests

No.	OCR	b_{cyc}	q^{ampl} (kPa)	CSR	ε_1^p ^a (%)	ε_2^p ^a (%)	No.	OCR	b_{cyc}	q^{ampl} (kPa)	CSR	ε_1^p ^a (%)	ε_2^p ^a (%)
D1	1	0	19.4	0.217	0.155	-0.077	D33	2	0.6	42.8	0.290	0.296	0.192
D2			24.0	0.269	0.346	-0.173	D34			48.4	0.328	0.363	0.168
D3			30.9	0.346	0.803	-0.402	D35			55.1	0.374	0.790	0.328
D4			33.0	0.370	1.492	-0.746	D36			61.6	0.417	2.320	0.888
D5			34.4	0.386	5.505	-2.753	D37			69.5	0.472	6.546	2.231
D6	1	0.4	19.4	0.217	0.102	-0.009	D38	2	0.8	42.8	0.290	0.172	0.197
D7			24.0	0.269	0.260	-0.037	D39			48.4	0.328	0.268	0.161
D8			27.0	0.303	0.413	0.045	D40			55.1	0.374	0.394	0.367
D9			30.9	0.346	0.572	-0.124	D41			61.6	0.417	0.882	0.654
D10			33.0	0.370	0.941	0.004	D42			69.5	0.472	5.520	5.460
D11	1	0.8	34.4	0.386	1.701	-0.359	D43	4	0	40.4	0.186	0.220	-0.110
D12			19.4	0.217	0.050	0.044	D44			53.2	0.245	0.248	-0.124
D13			24.0	0.269	0.195	0.127	D45			66.0	0.304	0.449	-0.225
D14			30.9	0.346	0.341	0.298	D46			71.2	0.328	0.732	-0.366
D15			33.0	0.370	0.389	0.434	D47			80.5	0.371	2.774	-1.387
D16	2	0	34.4	0.386	0.616	1.267	D48	4	0.4	91.8	0.423	5.797	-2.898
D17			36.7	0.411	1.903	2.191	D49			53.2	0.245	0.184	0.300
D18			38.9	0.436	5.112	3.016	D50			71.2	0.328	0.551	0.181
D19			42.8	0.290	0.402	-0.201	D51			80.5	0.371	0.832	-0.011
D20			48.4	0.328	0.699	-0.349	D52			91.8	0.423	2.319	-0.155
D21	2	0.2	55.1	0.374	1.585	-0.793	D53	4	0.8	94.6	0.436	4.270	-0.331
D22			56.9	0.386	3.640	-1.820	D54			98.1	0.452	5.170	0.103
D23			42.8	0.290	0.377	-0.094	D55			53.2	0.245	0.121	0.200
D24			48.4	0.328	0.603	-0.228	D56			71.2	0.328	0.370	0.433
D25			55.1	0.374	1.263	-0.420	D57			80.5	0.371	0.501	0.939
D26	2	0.4	61.6	0.417	3.815	-1.325	D58	8	0.4	91.8	0.423	1.228	1.186
D27			69.5	0.472	7.033	-1.335	D59			98.1	0.452	3.096	3.367
D28			42.8	0.290	0.326	-0.010	D60			76.7	0.224	0.239	-0.294
D29			48.4	0.328	0.471	-0.096	D61			102.0	0.298	0.614	-0.072
D30			55.1	0.374	0.996	-0.209	D62			115.4	0.337	0.957	0.153
D31	2	0.4	61.6	0.417	3.030	-0.247	D63	8	0.4	131.8	0.385	1.283	-0.103
D32			69.5	0.472	7.158	-0.239	D64			141.1	0.412	2.114	0.219
							D65			147.2	0.430	4.711	-0.161

Note: ^a ε_1^p at the end of tests, ^b ε_2^p at the end of tests

Table 2. The predicted values of A and B , and the percentage difference between the predicted ε_1^p by Eqs.

6 and 9

	N	A	B	The percentage difference ($b_{cyc}=0$)	The percentage difference ($b_{cyc}=0.4$)	The percentage difference ($b_{cyc}=0.8$)
OCR=1 CSR=0.346	50,000	-0.755	1.004	-14.7 %	-5.6 %	-6.5 %
	250,000	-0.951	1.220	-29.6 %	-13.3 %	-15.1 %
	1000,000	-1.119	1.406	-41.8 %	-21.2 %	-23.0 %
OCR=2 CSR=0.328	50,000	-0.675	0.861	-8.1 %	-0.02 %	-13.4 %
	250,000	-0.807	1.027	-19.2 %	-6.8 %	-25.9 %
	1000,000	-0.920	1.170	-29.2 %	-14.1 %	-36.5 %
OCR=4 CSR=0.328	50,000	-0.541	0.870	-5.6 %	-2.5 %	-2.3 %
	250,000	-0.639	1.013	-13.2 %	-8.1 %	-8.0 %
	1000,000	-0.723	1.136	-20.5 %	-14.0 %	-13.8 %

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Fig. 5. The accumulation of permanent strains under OCR=4 and CSR=0.328 for tests: (a) $b_{cyc}=0$; (b) $b_{cyc}=0.4$ and (c) $b_{cyc}=0.8$

Fig. 6. Influence of the stress paths on the strain paths for tests: (a) OCR=1, CSR=0.269; (b) OCR=1, CSR=0.370; (c) OCR=4, CSR=0.371 and (d) OCR=4, CSR=0.423

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