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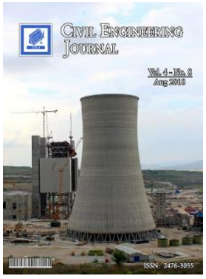

Effect of Cyclic Stress Level and Overconsolidation Ratio on Permanent Deformation Behaviour of Clayey Subsoil

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Abstract

This paper presents the results of a series of one-way cyclic triaxial tests carried out to investigate the role of cyclic stress level and overconsolidation ratio (OCR) on the permanent deformation behaviour of saturated clayey subsoil during long-term cyclic loading. Based on the test results and shakedown concept, two cyclic threshold deviator stress ratios can be defined: the plastic shakedown limit cyclic deviator stress ratio CSRpt (0.46) and the plastic creep shakedown limit cyclic deviator stress ratio CSRpc (0.75). It was found that, below CSRpt, the soil experiences slight deformation and gradually achieves a long-term steady state response. Within the range of CSRpt<CSR<CSRpc, the plastic strain will accumulates substantially and becomes unstable. Once the CSRpc is exceeded significant deformation and failure may occur. In the practical engineering, CSRpt can be used for preliminary design of pavement foundation. In addition, based on the test results, a simplified permanent axial strain model that explicitly considers the effects of CSR and OCR is developed.

Keywords: Saturated Clayey Subsoil; Cyclic Stress Ratio; Overconsolidation Ratio; Permanent Axial Strain; Explicit Model.

1. Introduction

The development of modern transport infrastructures (motorways, railways, ports, and airports) across the deep soft clay outcrops encountered in southeast China, has led to the construction of embankments on soft ground with poor geotechnical characteristics, namely with low shear strength and high compressibility. When the organic content of these soils is high, notable creep settlement can also be observed, which contributes to an increase in the maintenance costs over exploitation time and can even compromise the functionality of the structure [1]. Some improvement techniques, such as the preloading by mechanical surcharging, by using vacuum are usually used applied to attenuate the creep effects of the soft ground. However, vast engineering practice indicates that although the creep settlement is less due to the foundation reinforcement, during their operational life they are subject to a large number of repeated loads, which under unfavorable conditions can result in the accumulation of unacceptably large plastic strains [2]. For example, the Shanghai Metro Line-1 showed modest (2-6 mm) settlements at multiple locations over the 2 years between its construction end and operational opening. However, an unfavorable excessive settlement of 60 mm was developed over the first 8 months of service and an additional 180 mm over 18 years of operation [3]. Despite the incomplete consolidation and creep settlement, the permanent deformation induced by long-term traffic loading is an important component of the total subgrade settlement. Therefore, it is of scientific value and practical significance to investigate the deformation behaviour of soft clays under traffic loading. The dynamic response (cyclic degradation and cyclic pore water pressure) of soft clay under cyclic loading have been studied in considerable depth in the past, many threshold stress level [4] and empirical formulas for deformation predictions have been proposed [5].

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Brown and Selig (1991) observed that there is a threshold stress level above which significant plastic axial strain and (in undrained conditions) generation of excess pore water pressure occurs. Below this threshold stress, changes in permanent axial strain and pore water pressure are very small or negligible [6]. Cheung (1994) suggested the concept of a limiting value of q/q_f (i.e., $q_{threshold}/q_f$), which occurs at the cyclic stress required to generate 1% permanent strain in a sample following 1,000 applications. Beyond $q_{threshold}/q_f$, plastic deformation increases relatively rapidly [7]. For analytical pavement foundations design, Brown (1996) suggested that the dominant factor in determining permanent deformation is the relationship between applied cyclic deviator stress (q_{cyc}) and the undrained shear strength of the soil (i.e., stress ratio, q/q_f) [8]. Frost et al. (2004) suggested a value of applied cyclic deviator stress above which the onset of permanent deformation becomes unstable is shown to occur approximately at 50% of the deviator stress at failure ($0.5q_f$) and proposed a simplified design approach for preliminary designs of pavement [9]. Similarly, based on tests with a significantly larger number of cycles (N=50,000), Guo et al. (2013) also proposed a CSR called “allowable CSR” for Wenzhou subgrade soft clay to guide a more practical design for the engineering structures under traffic loading [10].

In addition to threshold cyclic stress ratio (CSR_t), the existence of CSR_c was confirmed by the cyclic tests results from Mitchell and King [11], Zhou and Gong (2001) and Boulanger and Idriss (2007) in investigating the dynamic response of soils to seismic loading[12,13]. Above this level, a soil fails after dozens of cycles. According to the shakedown concept, Tang et al. (2015) proposed three cyclic stress limits of the soft clay subsoil and used to determine the corresponding depths of influence [14]. Although a number of investigations have considered the effects of cyclic loading on soil behaviour, but the threshold cyclic stress ratio have not been adequately investigated, relatively few have addressed the effect of overconsolidation ratio. A systematic investigation of threshold cyclic stress ratio in overconsolidated (OC) clay has not been conducted.

Traditionally, empirical approaches have also been employed to predict the traffic-load-induced permanent axial strains of pavement, a number of empirical equations have been proposed in the literature [15-20], and while they have different forms, they all seem to give reasonable results. These excellent works provide fundamental tools for further understanding the cyclic behaviour of soft clays, which is of significance in practical design methods for the high-speed traffic subgrade. However, most of these studies were performed on normally consolidated (NC) clays. Overconsolidated (OC) clays show very distinctive mechanical properties when compared to normally consolidated (NC) clays, including reduced compressibility, increased strength, and increased stiffness. Important permanent structures such as high-speed railways are extremely sensitive to differential settlements, which must be kept within an extremely small range in order to ensure the operational requirements when constructed on overconsolidated soils. Both field measurements [21, 22] and laboratory tests [23, 24] have pointed out that the amount of settlement which occurs after road construction depends strongly on the overconsolidation ratio. To date, an accurate prediction equation that can explicitly include the effect of overconsolidation has not been reported for long-term of intensive traffic.

Owing to the limited amount of laboratory test data available, uncertainties remain in our understanding of the overconsolidation ratios and magnitudes of cyclic deviator stress for the long-term permanent deformation behaviour of subgrade soils of transport infrastructures. The aim of the research reported in this paper was to evaluate the relative response of the one-way cyclic behaviour of normally consolidated (NC) to heavily Overconsolidated (OC) Wenzhou soft clay by applying a wider range of cyclic deviator stress levels in undrained conditions using an advanced cyclic triaxial device. The influence of CSR and OCR on the development of permanent axial strain have been interpreted and discussed with their practical implications. Based on the test results and shakedown concept, two cyclic threshold deviator stress ratios was defined and a simplified permanent axial strain model that explicitly considers the effects of CSR and OCR values is proposed for the deformation behaviour of clayey subsoil under traffic loading.

2. Test Equipment and Test Scheme

The laboratory tests were carried out using an advanced cyclic triaxial device, which was designed and manufactured by GDS Corporation in Great Britain described by Gu et al.(2016) [24]. In this apparatus, the vertical stress is applied by a servo-loading system, while the confining pressure is supplied through an oil pressure type of piston. Images of the cyclic triaxial device and schematic diagram of the apparatus is shown in Figure 1.

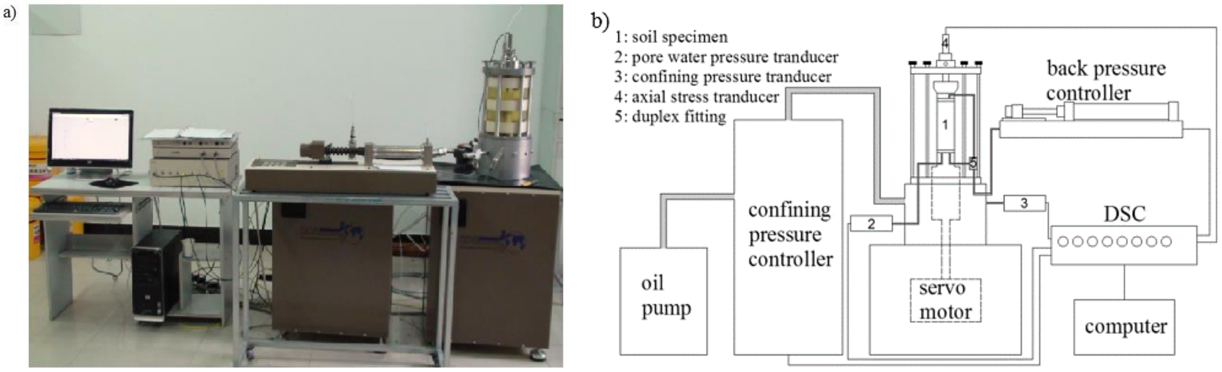

Figure 1. (a) General view of the apparatus; (b) Schematic diagram of advanced cyclic triaxial device

To minimize the variability inherent to the use of undisturbed samples, remolded samples were used this experimental investigation. The natural soil was obtained at the bottom of a deep excavation with a depth of 9-11 m in Wenzhou city, Zhejiang province of China, where problematic soils with high water content, high compressibility, low permeability and low bearing capacity are often encountered. The primary index properties are shown in Table 1. To prepare the remolded samples, the natural soil was initially dried in an oven and then ground to a powder, then it was mixed with enough distilled water to obtain a 1.5 liquidity index w_L and consolidated in a large consolidation vessel 20 cm diameter and 30 cm height under a one-dimensional consolidation pressure of 70 kPa, thus ensuring the destruction of the natural structure of the soil. Finally, cylindrical specimens of 5 cm diameter and 10 cm height were firstly hand-trimmed from the large cylindrical remolded samples, and then mounted in the triaxial cell. Following this, a back pressure of 300 kPa with an effective stress of 10 kPa was applied until B values greater than 0.98 were reached. Then, the specimens were isotropically consolidated under an effective confining pressure p'_0 of 100 kPa for 24 h to produce normally consolidated specimens. Overconsolidated specimens were obtained by consolidation to p'_{OC} =100 kPa × OCRs for 24 h and then unloading to p'_0 =100 kPa. The time allowed for swelling due to stress release was 1 h on average. After consolidation, strain-controlled monotonic triaxial tests or one-way stress-controlled cyclic triaxial tests were conducted under undrained conditions.

Table 1. The primary index properties of tested soft clay

Index properties	Values
Specific gravity, G_s (g/cm^3)	2.69~2.72
Natural water content, w_n (%)	59~63
Initial density, ρ_0 (g/cm^3)	1.62~1.67
Initial void ratio, e_0	1.64~1.71
Liquid limit, w_L (%)	60
Plasticity index, I_p	32
Clay fraction, (%)	41
Silt fraction, (%)	55
permeability coefficient, k_v (cm/s)	2.5×10^{-6}

To study how overconsolidation ratios and stress levels affected the permanent deformation behaviour of saturated soft clay in undrained condition, one-way stress-controlled cyclic loading tests with different overconsolidation ratios (OCR=1, 1.5, 2, 4) were performed by applying various amplitudes of deviator stress, with a frequency f=0.1 Hz. It is noted that the experiment results by Gu et al. (2016) revealed that the ultimate static deviator stress at failure q_f at OCR=1, 1.5, 2, 4 are 72.2, 89.6, 104.4 and 150.8 kPa, respectively [24]. Thus, in order to compare the cyclic behaviour of specimens with different OCR values, the cyclic stress ratio (CSR) was selected to serve as the normalized parameter, which is defined as the ratio of cyclic shear stress, q_{cyc} applied during the cyclic shear tests to the static deviator stress at failure q_f.

$$CSR = \frac{q_{cyc}}{q_f} \tag{1}$$

All the tests were performed at room temperature (approximately 20℃) according to the annual average temperature of Wenzhou. Figure 2 shows a schematic plot of the cyclic loading applied during the undrained cyclic traxial tests. The detailed test program is illustrated in Table 2.

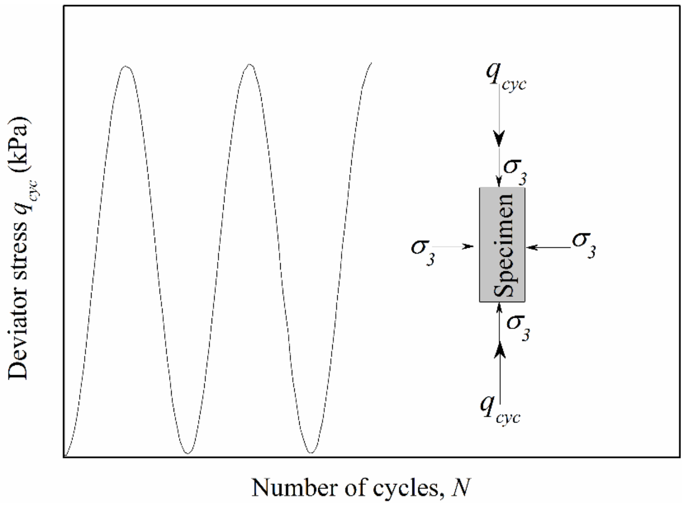

Figure 2. Schematic plot of advanced cyclic loading applied during the undrained cyclic traxial tests

Table 2. Conditions for Undrained Cyclic Triaxial Tests

File name	CSR (q_{cyc}/q_f)	OCR	Number of load cycles
NC1-1	0.208	1	5,000
NC1-2	0.277	1	5,000
NC1-3	0.36	1	5,000
NC1-4	0.526	1	5,000
NC1-5	0.596	1	5,000
NC1-6	0.651	1	5,000
NC1-7	0.762	1	5,000
NC1-8	0.831	1	2,000
OC1.5-1	0.223	2	5,000
OC1.5-2	0.36	2	5,000
OC1.5-3	0.55	2	5,000
OC2-1	0.297	2	5,000
OC2-2	0.36	4	5,000
OC2-3	0.614	4	5,000
OC4-1	0.278	4	5,000
OC4-2	0.36	4	5,000
OC4-3	0.543	4	5,000

3. Test results and Discussion

3.1. Typical Cyclic Triaxial Compression Test Results

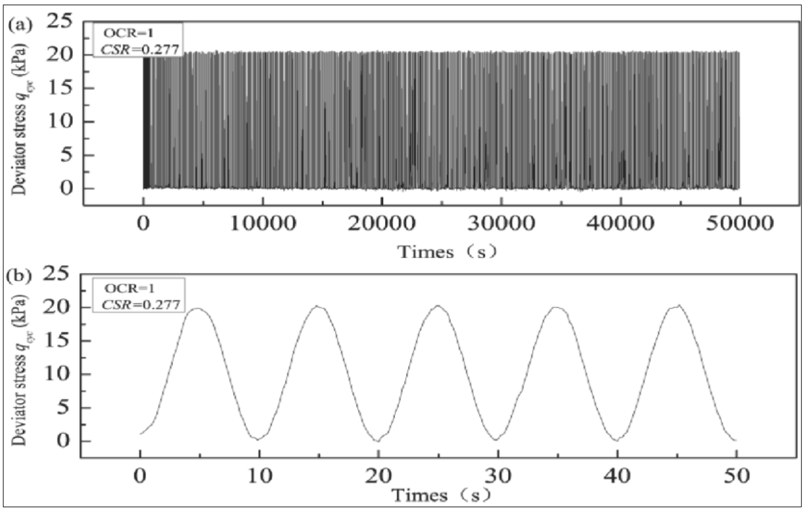

Figure 3. Variation of stress with time in a cyclic stress-controlled test on the NC1-03 specimen: (a) 50000s; (b) 50s

The actual applied loading with time in a cyclic stress-controlled test on the NC1-03 specimen is shown in Figure 3. It can be seen that the actual applied waveform is stable and reliable.

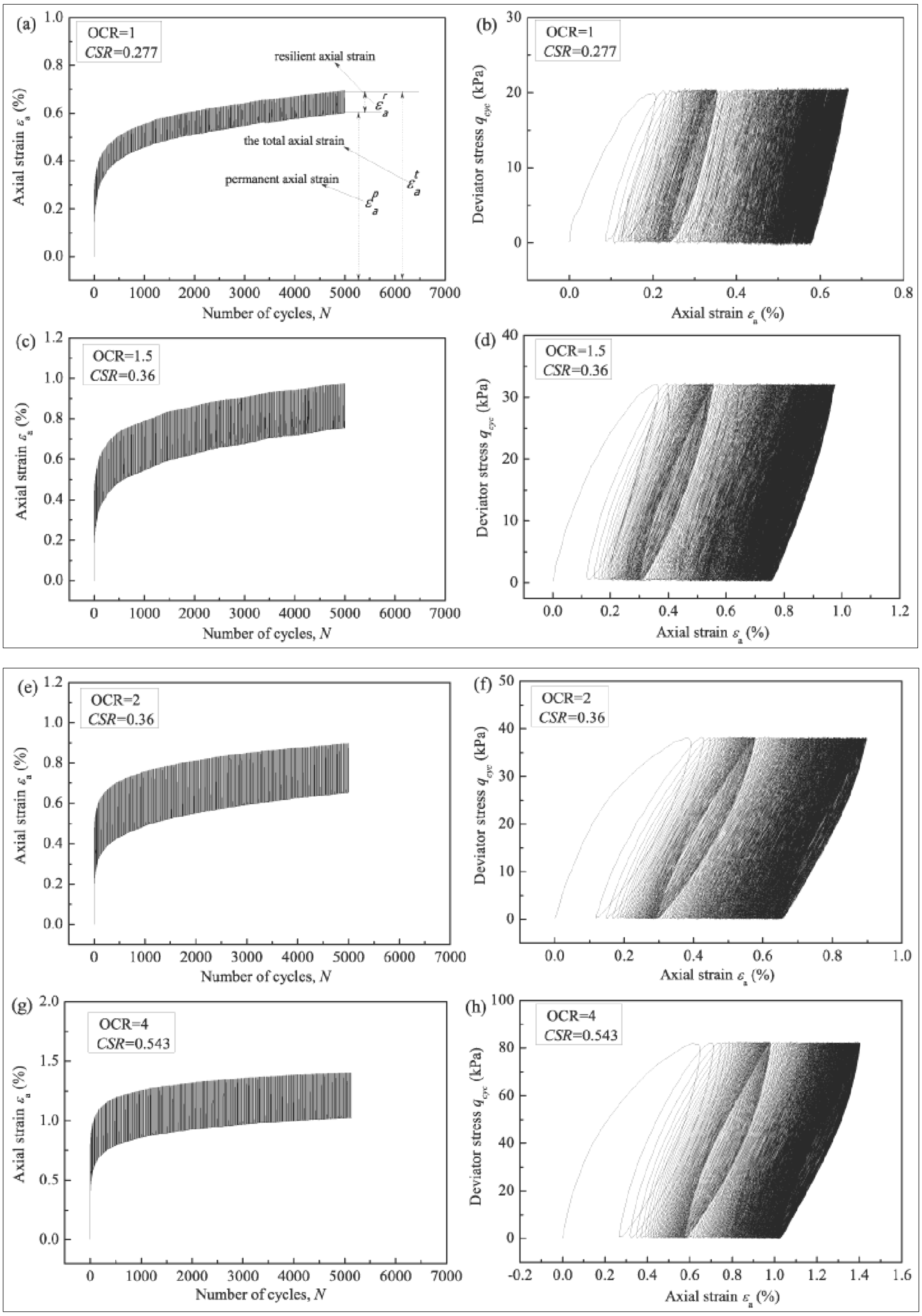

Figure 4. Results of cyclic test on the typical NC and OC specimens

Cyclic tests were carried out under undrained conditions, a total of 5,000 cycles were performed on each test specimen, except for specimen NC1-8, which failed after 2000 cycles. Figure 4 illustrates the typical variation of axial strain with the number of cycles and q_{cyc} versus axial strain on typical NC and OC specimen of Wenzhou clay under one-way cyclic loading. As shown in Figure 4(a), (c), (e), (g) the axial strain (ε_a) increase monotonically as N increased up to 5,000 cycles and exhibit a significantly cyclic response (resilient strain) during cycling, and the specimen remained stable. Figure 4(b), (d), (f), (h) present the typical characteristics of relationship between the cyclic deviator stress and the axial strain under undrained condition. The hysteresis loops move to the right continuously and incline to the horizontal direction gradually with the number of cycles, indicating the occurrence of strain softening, which result in the cumulative deformation of the specimen.

3.2. Permanent Axial Strain

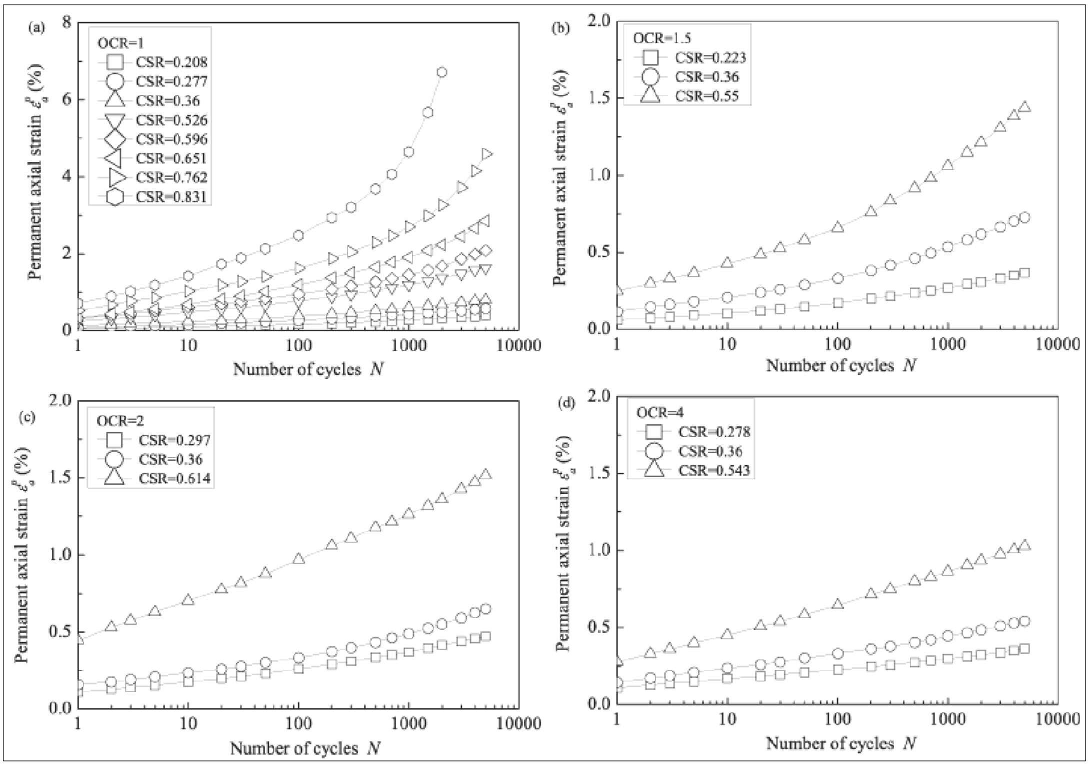

Figure 5. Accumulation behaviour of permanent axial strain: (a) OCR=1; (b) OCR=1.5; (c) OCR=2; (d) OCR=4

Figure 5 presents the resulting permanent axial strain curves ε^p_a (N) in a semi-logarithmical diagram. As a whole, it can be seen that higher stress ratio cause larger accumulation rates regardless of the OCR values. It is shown in Figure 5(a) and 5(b) that the curves are similar and the accumulation of permanent axial strain increases proportional to the logarithm of the number of cycles up to N ≈1,000 cycles and then over-proportionally. However, as shown in Figure 5(c) and 5(d), it is noted that the accumulation of permanent axial strain approximately linear with the logarithm of the number of load applications for all the stress ratios. It is indicated that higher OCR values (for example, OCR=2 and 4) have a certain influence on the shape of permanent axial strain ε^p_a -logN curves in undrained condition.

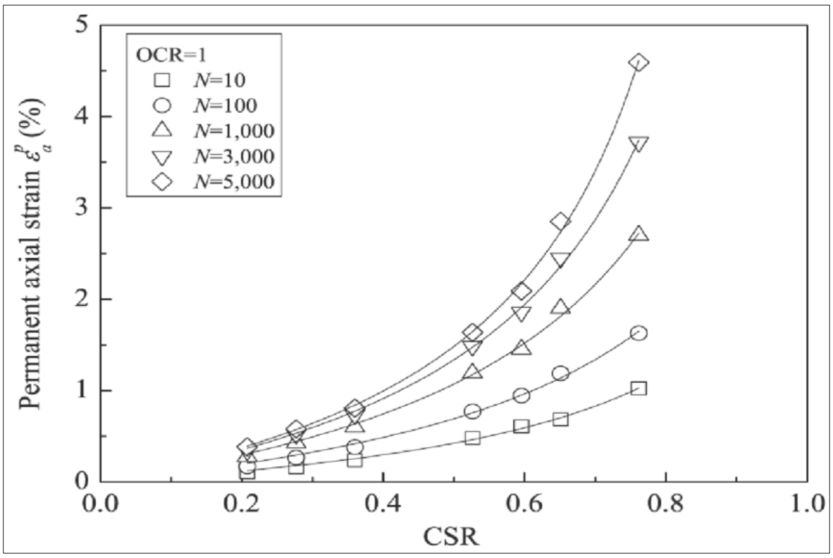

Figure 6. Permanent axial strain εpa of normally consolidated samples as a foundation of CSR for different numbers of cycles N

In Figure 6 the accumulated permanent axial strain after different numbers of cycles is plotted versus the cyclic stress ratio. The increase of permanent axial strain $\varepsilon^p_{a,N}$ with CSR can be expressed (solid curves in Figure 6) by a hyperbolic function as:

$$\varepsilon_{a,N}^{p} = \frac{a_N CSR}{1 - b_N CSR} \tag{2}$$

Where hyperbolic parameters a_N and b_N could be formulated as functions of N as defined in Figure 7.

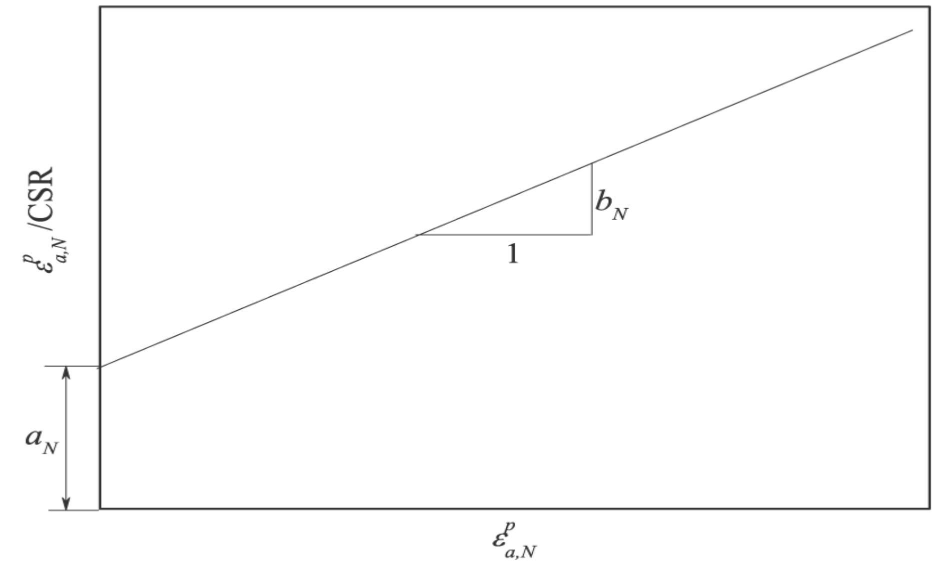

Figure 7. Definition of hyperbolic parameters a_N and b_N

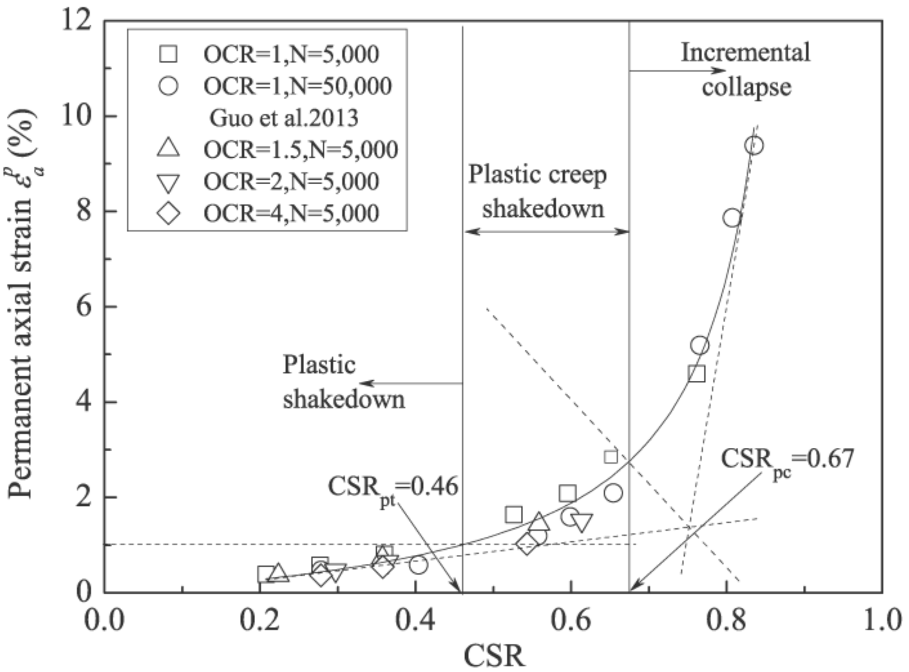

Figure 8. Permanent axial strain after 5,000 cycles versus CSR

Permanent axial strain after 5,000 cycles (f=0.1Hz) in this study for different OCRs and permanent axial strain after 50,000 cycles (f=1Hz) for normally consolidated specimens performed by Guo et al. (2013) [10] are plotted against the CSR values in Figure 8. One point to note is that although the cycles are different due to different cyclic loading frequency, but the total load time are the same. The diagrams in Figure 8 can be used to estimate the ‘‘threshold stress ratio’’. The approach suggested by Cheung (1994) [7]was used to determine the threshold stress from the permanent axial strain in Figure 8, i.e., defining the threshold as the cyclic deviator stress at which 1% permanent axial strain was reached. CSR value defined in this way is about 0.46 termed the “plastic shakedown threshold stresses ratio” CSR_{pt}, Below the cyclic stress ratio CSR_{pt} (0.46), the cumulative permanent axial strain of soils at different overconsolidation ratios was stable over a large number of loading cycles, and this behaviour is consistent with the plastic shakedown behaviour according to the shakedown concept. A approach similar to that used by Mitchell (1977) [11] (i.e. by locating the points at which the experimental stress–strain curves showed a marked bend) was used to determine a threshold stress ratio from the diagram in Figure 8, it consists basically in locating the marked bend point at the intersection of the rectilinear extrapolations of the pre- and post- increase portions of the ε^p_a–CSR curve. As the curves were non-linear from the beginning, some subjectivity was unavoidable in locating the marked bend point. By this approach, the CSR value correspond to the marked bend point of the ε^p_a–CSR curve in Figure 8 is about 0.67 termed the "plastic shakedown creep threshold stresses ratio" CSR_{pc}. When 0.46<CSR<0.67, the samples experience significant and continuous accumulation of permanent axial strain with number of cycles, and this behaviour is consistent with the plastic shakedown creep behaviour according to the shakedown concept. It can be predicted that the cumulative permanent axial strain would exceed 5% with increasing number of loading cycles, which is occasionally adopted as a sign of failure [14]. Once the cyclic stress ratio CSR_{pc} (0.67) was exceeded, small increases in cyclic deviator stress could trigger the rapid deterioration and failure of the previously stable soft subsoil, such behaviour is correspond to the incremental collapse stage of the shakedown concept. Through the above analysis, it is suggested that CSR_{pt}=0.46 would be suitable for preliminary design threshold stress of subgrade; CSR_{pt} (0.46) <CSR<CSR_{pc} (0.67) would be suggested as a warning before subgrade invalidation; CSR_{pc}=0.67 can be used as a sign of failure of the subgrade.

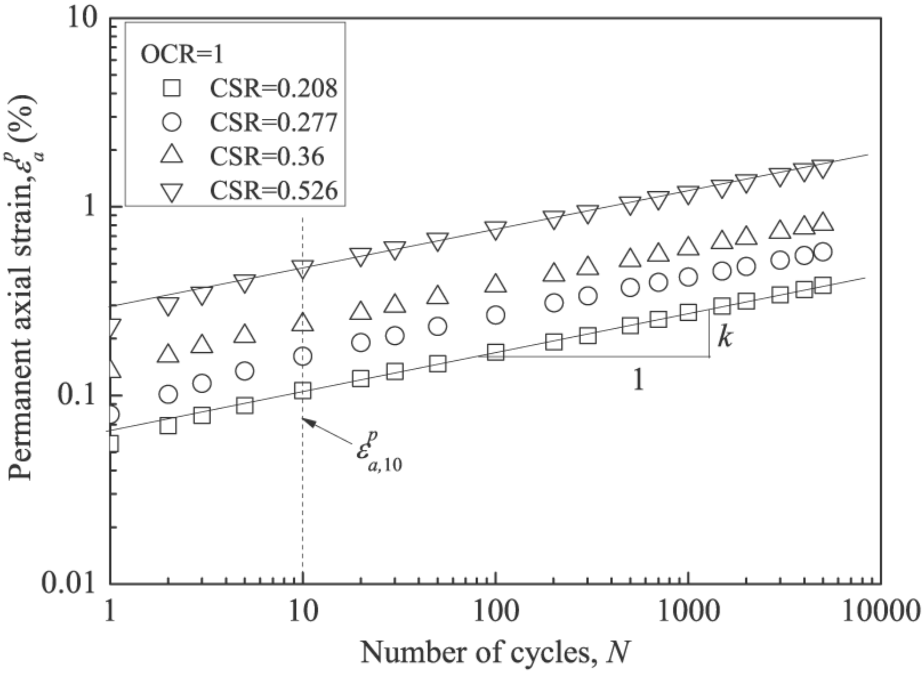

Figure 9. Development of Permanent axial strain with increasing number of cycles in log–log coordinates

The increase of the permanent axial strain with increasing number of cycles in tests at OCR=1 with different CSR below CSR_c (0.67) is presented in Figure 9. In a log–log plot, it can be seen that the curves are non-linear from the beginning to about N=10, while a nearly linear relationship is found between $\log\varepsilon^p_a$ and logN after N=10. A fitting equation for the permanent axial strain prediction can be established as:

$$\log \varepsilon_a^p = \log \varepsilon_{a,10}^p + k \log(\frac{N}{10}) \tag{3}$$

In which $\varepsilon^p_{a,10}$ is the permanent axial strain at N=10, k is the slope of linear relation which is independent of the value of CSR, in other words, k can be referred to as a material constant, In general, for Wenzhou soft clay the k value to be applied in Equation (2) can be determined as the mean value of 0.2. The permanent axial strain $\varepsilon^p_{a,10}$ is a function of CSR, according to previous discussion, the hyperbolic function (Equation 2) provides a better representation of the permanent axial strain. Where a_{10}=0.41, and b_{10}=1.05, respectively for Wenzhou clay in undrained conditions.

The final prediction equation for the permanent axial strain can be obtained by substituting Equation (2), a_{10}=0.41, b_{10}=1.05 and k=0.2 into Equation (3).

$$\varepsilon_a^p = \frac{0.41CSR}{1-1.05CSR}(\frac{N}{10})^{0.2} \tag{4}$$

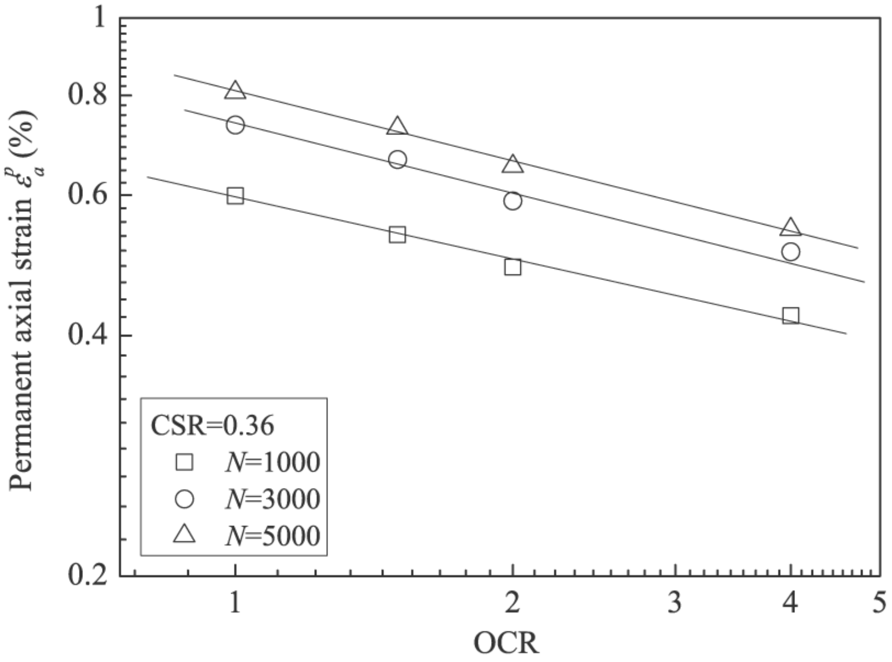

Figure 10. Permanent axial strains versus OCR values (CSR=0.36)

Figure 10 presents the permanent axial strains versus OCR values for certain numbers of cycles (N = 1000, 3000, and 5000) under the same CSR=0.36 in log–log coordinates. It is shown that for tests with the same CSR value, the logε^p_a–logOCR lines with different number of cycles are almost parallel to each other (i.e., identical inclinations). The normalized permanent axial strain ratio $\varepsilon^p_{a,OC}/\varepsilon^p_{a,NC}$ versus OCR values in log–log coordinates is given in Figure 11, a simple power function is adopted as follow:

$$\frac{\varepsilon^p_{a,OC}}{\varepsilon^p_{a,NC}} = OCR^m \tag{5}$$

Where $\varepsilon^p_{a,NC}$ is the permanent axial strain of normally consolidated clay under a constant cyclic stress ratio after a number of cycles N; and $\varepsilon^p_{a,OC}$ is the permanent axial strain of overconsolidated clay under the same conditions. The parameter m determined from the test results for Wenzhou soft clay in this study is about (-0.27).

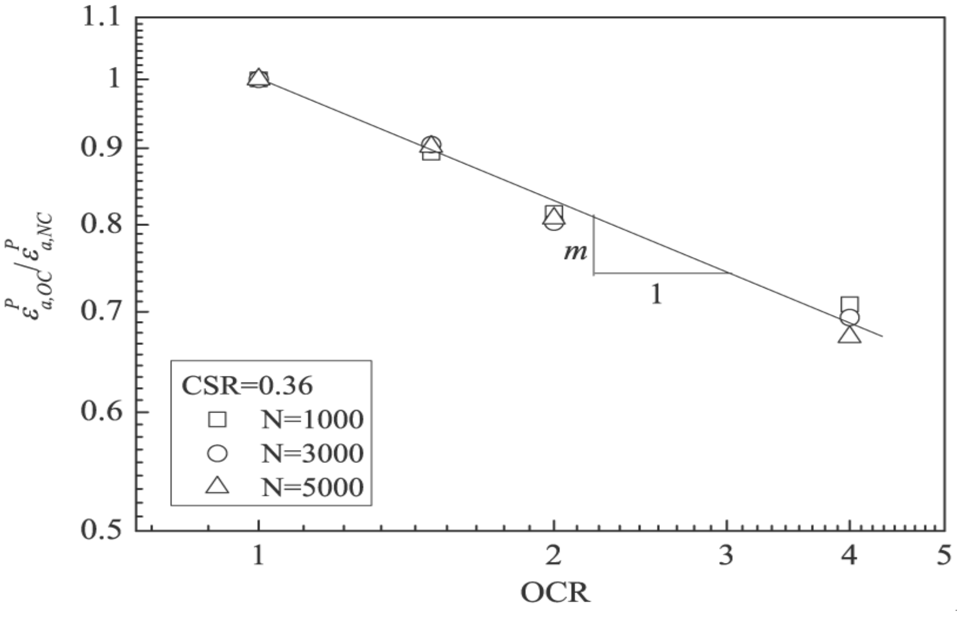

Figure 11. Relationship between normalized permanent axial strain ratio and OCR value

Based on Equation 4 and 5, the following empirical formula, which includes explicitly the effects of cyclic deviator stress and overconsolidation, is proposed to predict the permanent axial strain of Wenzhou soft clay:

$$\varepsilon_a^p = \frac{0.41CSR}{1-1.05CSR}\left(\frac{N}{10}\right)^{0.2} OCR^{-0.27} \quad (6)$$

The comparison between measured permanent axial strain and the prediction by Equation (6) is presented in Figure 12. The predicted results agree sufficiently well with the measured test data especially when the cyclic stress ratios below CSR_{pt}=0.46, implying a good prediction quality for the Wenzhou soft clay deformation under long-term one-way cyclic loading in undrained conditions.

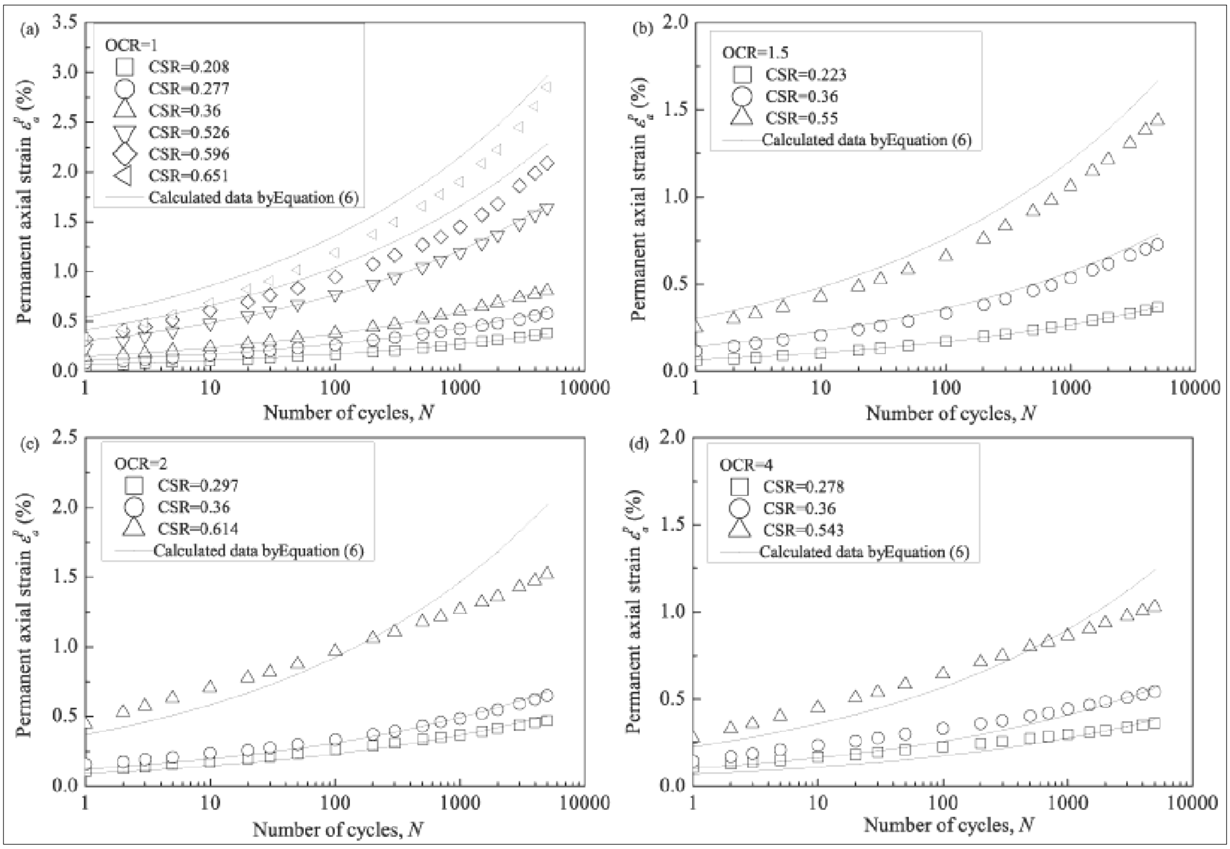

Figure 12. Comparison of calculated permanent axial strain and measured results: (a) OCR=1; (b) OCR=1.5; (c) OCR=2; (d) OCR=4

5. Conclusions

In this study, a series of undrained cyclic triaxial tests were carried out to investigate the effects of cyclic deviator stress levels and overconsolidation ratios on the permanent deformation behaviour of Wenzhou soft clay. The major conclusions can be concluded as below:

1) The development of permanent axial strains of Wenzhou soft clay depends on the magnitude of the cyclic deviator stress and overconsolidation ratio. In addition, the shape of the permanent axial strain ε^p_a -log$N$ curves is also influenced by the overconsolidation ratios.
2) According to the shakedown concept, two cyclic stress ratio CSR_{pt} (0.46) and CSR_{pc} (0.67) were obtained from cyclic triaxial tests results for Wenzhou soft clay, which can be used for preliminary design threshold stress of subgrade and a warning before subgrade invalidation;
3) Based on the test results, an empirical formula considering the effects of cyclic deviator stress and overconsolidation ratios is proposed to predict the permanent axial strain of normally consolidated to overconsolidated Wenzhou soft clay under one-way cyclic loading in undrained condition.

6. Acknowledgements

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