Study on the creep behavior of Tianjin marine soft clays and its improved Mesri model

Gang Li¹, Zhen Yan², Jinli Zhang³*, Jia Liu⁴ and Rui Liu¹
¹Shaanxi Key Laboratory of Safety and Durability of Concrete Structures, Xijing University, Xi’an, Shaanxi, 710123, China
²Tianjin Research Institute for Water Transport Engineering, Ministry of Transport, Tianjin, 300456, China
³State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian, Liaoning, 116024, China
⁴School of Geological Engineering and Geomatics, Chang’an University, Xi’an, Shaanxi, 710054, China
*Corresponding author’s e-mail: jlzhang@dlut.edu.cn

Abstract: Marine soft clays are widely distributed in coastal areas. Owing to their strong creep properties, soft clay foundations undergo significant post-construction settlement, thereby affecting the life cycle of buildings. In this study, the creep behavior of Tianjin marine soft clays was investigated by consolidated-undrained triaxial creep tests. Based on the creep test results and the Mesri creep model and by treating the final clay deformation under each increment of load as the initial strain, an improved Mesri creep model that describes both the stress-strain and strain-time relationships using hyperbolic functions was established. The creep curves under various levels of cell pressure and deviatoric stress showed notable decay and stable creep characteristics but contained no accelerated creep stage. The stress–strain isochronous curves exhibited notably nonlinear characteristics. Relative to the results calculated by the Singh–Mitchell and Mesri models, the results calculated by the improved Mesri model were in better agreement with the test results, which suggests that the established model is suitable for describing the creep behavior of Tianjin marine soft clays and can provide a reference for predicting the long-term settlement of foundations.

1. Introduction
As urbanization accelerates, there are increasingly fewer land resources suitable for engineering construction. In coastal areas, large numbers of roads, railroads, ports, docks and airports are built on soft clay foundations. Soft clays have a high water content, high void ratios, high compressibility, low shear strength, low permeability and strong creep properties. Excessive post-construction settlement of soft clay foundations results in a series of safety hazards to engineering construction. Wang et al.[1] studied the effects of the stress–dilatancy relationship on the evolution of strains and excess pore pressure by conducting undrained triaxial creep tests on a soft clay. They applied a modification method for the stress dilatancy of sands to the clay and found that the modified dilatancy equation with the inclination of a potential surface could satisfactorily describe the undrained creep process of the clay. Cetin et al.[2] comparatively analyzed structural changes in a soil during drained and undrained triaxial creep tests and noted that failure occurred at high levels of strain during the
undrained tests and at low levels of strain during the drained tests. They found that a larger deformation area was formed at the location of failure during the drained tests. These results occurred because soil particles had sufficient time to respond to the shear stress and could gradually alter their orientation. Lai et al.\cite{3} conducted triaxial creep tests that considered the effects of suction to investigate the effects of water content on long-term deformation of landslide masses. The test results showed that in a double-logarithmic coordinate system, the axial strain increased linearly, and the axial strain rate decreased linearly as time increased; the axial strain and axial strain rate increased as the level of deviatoric stress increased and the suction decreased. Based on an empirical creep model for saturated soils and by considering the linear relationship between suction and model parameters, they established a corrected model that considers the effects of suction. Chen et al.\cite{4} studied the creep behavior of a soft soil by triaxial creep tests and found that the level of stress significantly affected the creep behavior of the soil. Specifically, under low levels of stress ($S=0.1$), soil particles displayed notably elastic properties and did not undergo significant creep deformation. Under moderate levels of stress ($0.2<S<0.6$), the creep curves showed a notable linear viscoelastic stage. Under high levels of stress ($S>0.8$), the creep curves showed a nonlinear viscoelastic stage. Under a level of stress of 1.0 ($S=1.0$), creep failure occurred during the initial phase of the accelerated creep stage.

A large variety of rheological models have been developed based on creep test results. Overall, these models can be categorized into four types, namely element models\cite{5-9}, yield surface models\cite{10-14}, endochronic models\cite{15-17} and empirical models\cite{18-22}. Widely used empirical models include power function, hyperbolic, exponential, logarithmic and polynomial models. Wang et al.\cite{23} studied the triaxial creep behavior of a saturated clay under single- and multi-stage loading conditions and established a strain-rate- and stress-dependent coupled creep model in which the creep rate is a function of inelastic strain and effective stress. Zhu et al.\cite{24} investigated the creep behavior of unsaturated weak intercalated soils using a GDS triaxial apparatus and established an improved Mesri model that can take into consideration the stress–strain–time relationships. They found that the creep behavior of the intercalated soils was affected by the matric suction. By fitting the improved Mesri model to the test results, they discovered that the parameters $E_d$ and $m$ of the model were correlated with the matric suction $s$ and the stress level $D$ and that the predictions from the improved Mesri model were better than those of the Mesri model. Based on triaxial creep test results for an artificially frozen soil and the Nishihara model, Li et al.\cite{25} established a constitutive model that conforms to the parabolic yield criterion. This model is suitable for analyzing long-term stability of frozen soils and predicting their deformation. To avoid excessive post-construction settlement, Zhu et al.\cite{26} studied and used a fractional Merchant model to describe the creep behavior of Nansha clay.

In this study, undrained triaxial creep tests were conducted on remolded specimens of Tianjin muddy marine clays under various levels of cell pressure and deviatoric stress to examine the strain–time, strain–deviatoric stress and strain rate–time relationships. Based on the creep test results, an improved piecewise-fitting Mesri model was established to provide guidance for predicting the long-term settlement of soft clay foundations in the coastal area of Tianjin.

2. Soils and Testing Methods

2.1 Test specimens

Soil specimens (muddy clay specimens in a fluid-plastic state) were collected at depths ranging from 5 to 10 m at the Tianjin Port. Saturated remolded specimens with a dry density of 1.25 g/cm$^3$ were prepared by subjecting disturbed soil specimens to a series of treatments (e.g., drying, grinding, sieving, and remolding) according to the Specification of Soil Test (SL237-1999). During the preparation process, the specimens were saturated using the pumping saturation method. The specimens stood still underwater for more than 10 h. Table 1 summarizes the basic physical properties of the specimens.
Table 1 Physical properties of remoulded soil

| $\gamma$ (g/cm$^3$) | $\gamma_d$ (g/cm$^3$) | $\omega$ (%) | $S_r$ (%) | $e$  |
|---------------------|----------------------|-------------|-----------|-----|
| 1.8201              | 1.2499               | 45.62       | 100       | 1.316|

2.2 Test equipment and testing program

An SLB-1 stress-strain-controlled triaxial shear penetration test system (manufactured by Nanjing Soil Instrument Factory Co., Ltd.) was used. This system is strain- or stress-controlled and can be used to conduct unconsolidated-undrained, consolidated-undrained and consolidated-drained tests, anisotropic and isotropic consolidation tests, back-pressure saturation tests, $K_0$ tests, stress path tests and creep tests. This system consists mainly of an axial loading system, a cell pressure measuring system, a back-pressure control and measuring system, and a volume and pore water pressure control and measuring system.

Each specimen had a diameter of 39.1 mm and a height of 80 mm. During each test, the saturated remolded specimen was placed on the base of the triaxial pressure chamber. In addition, porous stones and filter paper were placed immediately above and beneath the specimen. The specimen cap was tied to the base of the apparatus using a rubber membrane. Subsequently, the cell pressure and pore pressure control and measuring system were used to apply cell pressure to the soil specimen to consolidate it. The consolidation time was set to 24 h. A five-stage loading approach was adopted for each creep test. Based on the in situ stress state of the soil, three levels of cell pressure were used, namely, 50, 100 and 150 kPa. Based on the deviatoric stress ($q_f$) at failure in a consolidated-undrained shear test under the same cell pressure, the load increment for each soil specimen at each stage was determined (load increment: $q_f/5$). The loading time for each stage was set to 48 h. During each test, the temperature was controlled at 20±1°C. Table 2 summarizes the loading scheme.

Table 2 Loading scheme

| soil         | $\sigma_3$/kPa | $q$/kPa |
|--------------|---------------|--------|
|              | 1 stage | 2 stage | 3 stage | 4 stage | 5 stage |
| muddy clay   | 50      | 14      | 28      | 42      | 56      | 66      |
|              | 100     | 25      | 50      | 75      | 100     | 115     |
|              | 150     | 35      | 70      | 105     | 140     | 175     |

3. Test Results and Analysis

3.1 Relationships between the axial strain and time

(a) 50 kPa cell pressure  
(b) 100 kPa cell pressure
Figure 1 shows the axial strain–time curves under a cell pressure of 50, 100 and 150 kPa, obtained using the Chen’s method. As demonstrated in Figure 1, the creep curves displayed notably nonlinear characteristics. Under each increment of deviatoric stress, the axial strain changed significantly during the initial stage and slowly stabilized as time increased. Under each increment of deviatoric stress, the soil deformation displayed notable decay creep behavior. Overall, the soil deformation patterns were essentially consistent under various levels of cell pressure, and the deviatoric stress–deformation essentially stabilized within 3,000 min after application of a deviatoric stress. Based on the aforementioned analysis, Tianjin muddy marine clays exhibited typical nonlinear creep behavior, and their axial strain increased as the deviatoric stress increased and slowly stabilized. During the whole creep process, Tianjin muddy marine clays displayed decay creep behavior.

3.2 Relationships between the axial strain and deviator stress

Figure 2 shows the deviatoric stress–axial strain isochronous curves under a cell pressure of 50, 100 and 150 kPa, which were produced to analyze the stress–strain relationship of Tianjin muddy marine clays. As demonstrated in Figure 2, the stress–strain relationship of the muddy clays displayed notably nonlinear characteristics. As the deviatoric stress increased, the axial strain gradually increased. Under a low level of deviatoric stress, the slope of the isochronous curve was small. As the deviatoric stress increased, the slope of the curve gradually increased, as did the corresponding axial strain. Similar to the creep behavior of a soft clay reported by Liu et al. [27], the isochronous curves at various times exhibited relatively consistent distribution patterns. When the deviatoric stress remained unchanged, the axial strain increased over time. When the axial strain remained unchanged, the deviatoric stress decreased over time. Based on the aforementioned analysis, Tianjin muddy marine clays exhibited typical nonlinear creep behavior, which became increasingly pronounced as the deviatoric stress increased.
3.3 Relationships between axial strain rates and time

Figure 3 shows the axial strain rate–time curves under a cell pressure of 50, 100 and 150 kPa. The strain rate decreased over time in a double-logarithmic coordinate system. The strain rate of the clays increased as the deviatoric stress increased. During the later stage of loading, the slopes of the curves under various levels of deviatoric stress were essentially the same. The $m$-value (the slope of the curve) ranged from 0.5 to 0.8, which suggests that the deviatoric stress had an insignificant impact on the $m$-value. In the whole creep process, the strain rate decreased over time. Tianjin muddy marine clays exhibited decay creep behavior, which corroborates the conclusions derived from the previous analysis.

4. Improved Mesri Model

An empirical model shows a stress–strain–time relationship determined by fitting indoor creep test results. The creep equation contains two parts: a deformation function (stress–strain relationship) and a creep function (strain–time relationship). The stress–strain relationship can be represented by a power, exponential or hyperbolic function. The strain–time relationship can be represented by a power,
logarithmic, exponential or hyperbolic function. The Singh–Mitchell and Mesri models\cite{20-22} are two representative empirical models.

4.1 Singh–Mitchell model

By summarizing drained and undrained triaxial compression test data obtained under single-stage constant loading conditions, Singh proposed an empirical creep model that describes the stress–strain relationship with an exponential function and the strain–time relationship with a power function. This model can satisfactorily describe the creep behavior of clays.

The Singh–Mitchell creep equation is as follows:

\[
\dot{\varepsilon} = A_r e^{\alpha D_r} \left( t / t_r \right)^m
\]

where \( \dot{\varepsilon} \) is the axial strain rate at any time \( t \); \( A_r \) is the strain rate at the unit reference time \( t_r \) when \( s_1 - s_3 = 0 \); \( \alpha \) is the slope of the linear section of the logarithmic strain rate–shear stress curve; \( D_r \) is the deviatoric stress level \( D_r = \left( \frac{s_1 - s_3}{s_1 - s_3} \right) f \), where \( \left( \frac{s_1 - s_3}{s_1 - s_3} \right) f \) is the failure deviatoric stress \( (q_f) \) for the soil specimen; \( t_r \) is the unit reference time; \( t \) is the creep time; and \( m \) is the slope of the linear section of the \( \ln \ln (t / \dot{\varepsilon}) \) curve.

By integrating Equation (1) \((m\neq1)\) and without considering the initial strain, we have

\[
\varepsilon = B e^{D_r \beta \left( t / t_r \right)^\lambda}
\]

where \( B = A_t t_r / (1 - m) \), \( \beta = \alpha \), and \( \lambda = 1 - m \).

When \( t = t_r \), Equation (2) can be rewritten as

\[
\varepsilon_r = B e^{D_r \beta}
\]

\[
\ln \varepsilon_r = \beta D_r + \ln B
\]

Based on Equations (3) and (4), \( \beta \) and \( B \) are the slope and intercept of the \( \ln \varepsilon_r \) curve when \( t_r = 1h \). Thus, the Singh–Mitchell creep model contains three parameters, namely, \( B, \beta \) and \( \lambda \), all of which can be obtained by fitting test data. Table 3 summarizes the parameters of the Singh–Mitchell model for cell pressures of 50, 100 and 150 kPa.

| Cell pressure | \( B \) | \( \beta \) | \( \lambda \) | Average \( \lambda \) |
|---------------|--------|--------|--------|--------|
| 50            | 0.255381 | 3.82   | 0.2746 | 0.1762 | 0.2070 | 0.2391 | 0.2153 |
| 100           | 0.261846 | 3.53   | 0.2534 | 0.1805 | 0.2002 | 0.2549 | 0.3179 | 0.2414 |
| 150           | 0.231772 | 3.67   | 0.2666 | 0.2109 | 0.1786 | 0.2235 | 0.2517 | 0.2263 |

Based on the parameters in Table 3, the triaxial creep process of the saturated remolded specimens of Tianjin muddy clays under cell pressures of 50, 100 and 150 kPa was separately calculated using the Singh–Mitchell model. Figure 4 compares the test results and the results calculated by the Singh–Mitchell model. The calculated results for low levels of deviatoric stress are consistent with the test results. However, the calculated test results for high levels of deviatoric stress match the test results poorly, which suggest that the Singh–Mitchell model is suitable for describing the creep behavior of remolded specimens of Tianjin muddy clays only under low levels of deviatoric stress.
Figure 4 Comparison between test and calculation by Singh-Mitchell model

4.2 Mesri model

The Mesri creep equation is as follows:

\[
\varepsilon = \frac{2}{E_u/S_u \cdot R_f \cdot D} \left( \frac{t}{t_1} \right) 
\]

(5)

where \(\varepsilon\) is the axial strain, \(t\) is the creep time, \(E_u\) is the initial tangent modulus, \(S_u\) is the shear strength, \(D\) is the shear stress level \([D=\left(\frac{1}{1}\right)\frac{1}{1} \left(\frac{1}{1}\right)]\), \(R_f\) is the failure stress ratio, \(t_1\) is the reference time, and \(\lambda\) is a test constant.

When \(t=t_1\), Equation (5) can be rewritten as

\[
\frac{\varepsilon}{D} = \frac{2}{E_u/S_u} + R_f \varepsilon 
\]

(6)

where \(\frac{2}{E_u/S_u}\) and \(R_f\) are the intercept and slope of the \(\frac{\varepsilon}{D}\) curve, respectively, and \(\lambda\) is the slope of the \(\log \varepsilon - \log \left( \frac{t}{t_1} \right)\) curve.

Thus, the Mesri creep equation contains three parameters, namely, \(\frac{2}{E_u/S_u}\), \(R_f\) and \(\lambda\), all of which can be determined by regression analysis of the test results. Table 4 summarizes the parameters of the Mesri model for cell pressure of 50, 100 and 150 kPa. Based on the parameters in Table 4, the triaxial creep process under a cell pressure of 50, 100 and 150 kPa was separately calculated using the Mesri model. Figure 5 shows the comparison of the test results and the results calculated by the Mesri model. The calculated results for low levels of deviatoric stress (first three increments of load) are consistent with the test results. However, the calculated results for high levels of deviatoric stress match the test results poorly, which suggests that (similar to the Singh–Mitchell model) the Mesri model is also
suitable for describing the creep behavior of remolded specimens of Tianjin muddy clays only under low levels of deviatoric stress.

Table 4 Mesri model parameters

| Cell pressure | $2/(E_u/S_u)$ | $R_f$ | $\lambda_1$ | $\lambda_2$ | Average $\lambda$ |
|---------------|---------------|-------|-------------|-------------|------------------|
| 50            | 2.07066       | 0.85063 | 0.2746      | 0.1762      | 0.1795           |
| 100           | 1.91692       | 0.82127 | 0.2534      | 0.1805      | 0.2002           |
| 150           | 1.80695       | 0.82320 | 0.2666      | 0.2109      | 0.1786           |

(a) 50 kPa cell pressure  
(b) 100 kPa cell pressure  
(c) 150 kPa cell pressure  

Figure 5 Comparison between test and calculation by Mesri model

4.3 Model establishment
Since neither the Singh–Mitchell model nor the Mesri model is completely suitable for describing the creep behavior of remolded specimens of Tianjin soft clays, based on the creep test results, a new creep model is established to describe the creep behavior of Tianjin soft clays.

$$\phi(t) = D(t)\psi(t)$$  \hspace{1cm} (7)

where $\phi(t)$ is a function related to deformation and stress at any time, $\psi(t)$ is a time function, and $D_r$ is the deviatoric stress level.

Vyalov proposed a general time function expression:

$$K(t) = \left(\frac{T_2}{T_1+t}\right)^n$$  \hspace{1cm} (8)

where $T_1$, $T_2$ and $n$ are all unknown parameters. Special cases of the function depend on the values of these three parameters. Based on the test curves with decay creep characteristics, the three parameters are set to the following values: $n=2$, $T_1=T$ and $T_2=\sqrt{T(\delta-1)}$. Thus, the following relationship is obtained:

$$\psi(t) = 1 + (\delta - 1)\frac{t}{T+t}$$  \hspace{1cm} (9)
where δ is the creep parameter.

By letting \(A = 2/(E_u/S_u)\) and substituting Equation (9) into Equation (7), we have

\[
\varepsilon = \frac{D_r A \delta(T + \delta t)}{(1 - D_r R_f) \delta T + (1 - D_r R_f \delta) \delta t}
\]

(10)

When \(t=0\), Equation (10) can be rewritten as

\[
\varepsilon_0^* = \frac{D_r A}{1 - D_r R_f}
\]

(11)

When \(t=\infty\), Equation (10) can be rewritten as

\[
\varepsilon_{\infty} = \frac{D_r A \delta}{1 - D_r R_f \delta}
\]

(12)

By combining Equations (10)–(12), we have

\[
\varepsilon = \varepsilon_0^* + (\varepsilon_{\infty} - \varepsilon_0^*) \frac{t}{T^* + t}
\]

(13)

where \(T^* = 1/ \left( \frac{1}{\varepsilon_0} \right) T\). Because a hyperbolic function displays decay characteristics, the above function is suitable for describing creep curves with decay creep characteristics.

The stress–strain function in the creep model is inapplicable to the initial phase of deformation of soft clays, which should be subjected to a piecewise analysis. Based on the tests conducted in this study, the time (2 min) at which the applied load is stable is treated as the point separating two stages. The strain \(\varepsilon_0\) at this time is treated as the initial strain. In addition, this time is treated as the start time of the creep stage. Thus, a new definition is required.

\[
\varepsilon_{\infty} - \varepsilon_0 = \frac{2}{E_u/S_u} \frac{D_r}{1 - R_f D_r}
\]

(14)

By rearranging Equation (13), an improved Mesri model is obtained:

\[
\varepsilon = \varepsilon_0 + \frac{2}{E_u/S_u} \frac{D_r}{1 - R_f D_r} \frac{t}{T^* + t}
\]

(15)

Thus, the improved Mesri creep model contains four parameters, namely \(\varepsilon_0\), \(2/(E_u/S_u)\), \(R_f\) and \(T^*\). Specifically, the initial strain \(\varepsilon_0\) is the strain when the load is stable; \(2/(E_u/S_u)\) and \(R_f\) are the parameters of the \((\varepsilon_{\infty} - \varepsilon_0)\)-\(D_r\) isochronous curve when time tends to infinity and have the same physical meaning as those in the Mesri model, and \(T^*\) is the creep parameter.

The following methods can be used to determine the parameters of the improved Mesri model.

1. Determination of \(\varepsilon_0\). According to the stress–strain isochronous curve, the duration between the beginning of each increment of load to the time when the load is stable is set to 2 min. Table 5 summarizes \(\varepsilon_0\) under each increment of deviatoric stress.

2. Determination of \(T^*\). By substituting Equation (14) into Equation (15), we have

\[
\varepsilon - \varepsilon_0 = (\varepsilon_{\infty} - \varepsilon_0) \frac{t}{T^* + t}
\]

(16)

Let \(\varepsilon_{\infty}^* = \varepsilon_{\infty} - \varepsilon_0\), \(Y = t/(\varepsilon - \varepsilon_0)\), \(a = t/\varepsilon_{\infty}^*\) and \(b = T^*/\varepsilon_{\infty}^*\). Equation (8) is transformed to a linear form \((Y = ax + b)\). Figure 6 shows the \(t/(\varepsilon - \varepsilon_0)\) curves obtained under various levels of cell pressure. \(T^*\) under each increment of load can be obtained by fitting the data in Figure 6 using the method of least squares.
(a) 50 kPa cell pressure  
(b) 100 kPa cell pressure  
(c) 150 kPa cell pressure

Figure 6 Relationship between $t/(t+\varepsilon_0)$ and $t$

Figure 7 Relationship between $\varepsilon^*/D_\varepsilon$ and $\varepsilon^*_\infty$

(3) Determination of $2/(E_u/S_u)$ and $R_c$. An $\varepsilon^*/D_\varepsilon - \varepsilon^*_\infty$ curve is plotted, as shown in Figure 7. The intercept and slope of the straight line fitted to the $\varepsilon^*/D_\varepsilon - \varepsilon^*_\infty$ curve are $2/(E_u/S_u)$ and $R_c$, respectively. Table 5 summarizes the model parameters for saturated remolded specimens of Tianjin soft clays for various levels of cell pressure.

Table 5 summarizes the model parameters for saturated remolded specimens of Tianjin soft clays for various levels of cell pressure.
4.4 Model verification

Based on the model parameters in Table 5, the creep test process was characterized using the improved Mesri creep model. Figure 8 shows the comparison of the test results and the results calculated by the model. The results calculated by the improved Mesri creep model are consistent with the test results. In particular, the predictions for high levels of deviatoric stress obtained using the improved Mesri model are notably superior to those obtained using the Singh–Mitchell and Mesri models, which suggests that the improved Mesri model is suitable for describing the creep behavior of remolded specimens of Tianjin muddy clays.

### Table 5 Improved Mesri model parameters for muddy clay in Tianjin Port

| $\sigma_3$/kPa | $2/(E_{u}/S_u)$/% | $R_1$ | 1 stage | 2 stage | 3 stage | 4 stage | 5 stage | Average $T$ |
|--------------|-----------------|-------|----------|----------|----------|----------|----------|------------|
| 50           | 1.7711          | 0.854 | 122.52   | 124.50   | 126.69   | 84.04    | 57.36    | 103        |
| 100          | 1.6643          | 0.831 | 156.48   | 178.72   | 107.19   | 70.78    | 122.52   | 126.9      |
| 150          | 1.6701          | 0.817 | 135.67   | 102.27   | 110.48   | 72.72    | 56.71    | 96.12      |

To further examine the reliability of the improved Mesri model, the creep test process of remolded specimens of muddy clays collected from the Beijiang Port and Tanggu shallow-sea area was calculated using the improved Mesri model. The test data were extracted from the paper published by Wang et al.\cite{28}. Based on the in situ stress state of the clays, two levels of cell pressure, namely, 25 and 100 kPa, were used. A four-stage loading scheme was adopted.

### Table 6 Improved model parameters for muddy clay in Beijiang Port and Tanggu shallow-sea

| Soil                          | $\sigma_3$/kPa | $2/(E_{u}/S_u)$/% | $R_1$ | Average value $T$ | $q$ | $\varepsilon_0$/% |
|-------------------------------|---------------|-----------------|-------|-------------------|-----|-------------------|
| Muddy clay in Tanggu shallow-sea | 25            | 1.9323          | 0.805 | 91                | 1.0450 |

Figure 8 Comparison between test and calculation by improved Mesri model in Tianjin Port

To further examine the reliability of the improved Mesri model, the creep test process of remolded specimens of muddy clays collected from the Beijiang Port and Tanggu shallow-sea area was calculated using the improved Mesri model. The test data were extracted from the paper published by Wang et al.\cite{28}. Based on the in situ stress state of the clays, two levels of cell pressure, namely, 25 and 100 kPa, were used. A four-stage loading scheme was adopted.

### Table 6 Improved model parameters for muddy clay in Beijiang Port and Tanggu shallow-sea

| Soil                          | $\sigma_3$/kPa | $2/(E_{u}/S_u)$/% | $R_1$ | Average value $T$ | $q$ | $\varepsilon_0$/% |
|-------------------------------|---------------|-----------------|-------|-------------------|-----|-------------------|
| Muddy clay in Tanggu shallow-sea | 25            | 1.9323          | 0.805 | 91                | 1.0450 |
Table 1: Properties of muddy clay in Beijiang Port

| Stage | Cell Pressure (kPa) | Deformation Parameter a | Viscous Coefficient b | Creep Time (min) |
|-------|--------------------|-------------------------|----------------------|-----------------|
| 1     | 100                | 3.0599                  | 0.405                | 146             |
| 2     | 25                 | 0.1065                  |                      |                 |
| 3     | 75                 | 0.2440                  |                      |                 |
| 4     | 100                | 0.3556                  |                      |                 |

(a) 25 kPa cell pressure

(b) 100 kPa cell pressure

Figure 9 Comparison between test and calculation by improved Mesri model of muddy clay in Beijiang Port and Tanggu shallow-sea

Figure 9 shows the comparison of the test results and the results calculated by the improved Mesri model. The results for the muddy clays under a cell pressure of 25 and 100 kPa calculated by the improved Mesri model are consistent with the test results, which suggests that the improved Mesri model is suitable for describing the creep behavior of remolded specimens of Tianjin clays.

5. Conclusions

The creep behavior of Tianjin muddy marine clays was investigated by undrained triaxial creep tests. Based on the creep test results, an improved Mesri model was established. The conclusions derived from this study are summarized as follows:

1. Tianjin muddy marine clays exhibited typical nonlinear creep behavior. Under each increment of deviatoric stress, the creep curve displayed typical decay creep characteristics. The deformation essentially stabilized within 3,000 min after application of a deviatoric stress.

2. A notably nonlinear stress–strain relationship was observed for Tianjin muddy marine clays. As the deviatoric stress increased, the axial strain gradually increased. Under low levels of deviatoric stress, the slope of the isochronous curve was small. As the deviatoric stress increased, the slope of the curve gradually increased.

3. The axial strain of Tianjin muddy marine clays decreased over time and increased as the deviatoric stress increased. During the later stage of loading, the slopes of the curves under various levels of deviatoric stress were essentially the same, suggesting that the deviatoric stress had an insignificant impact on the m-value.

4. By modifying the strain–time relationship to a hyperbolic function, an improved Mesri creep model was established. The creep test was calculated using the improved Mesri model. The results obtained using the improved Mesri model were consistent with the test results, thereby validating the reliability of the established model and suggesting that the model is suitable for describing the creep behavior of Tianjin marine clays.

Acknowledgments

This study was supported by the Special Fund for Scientific Research by Xijing University (XJ18T01), Special Fund for Scientific Research by Shaanxi Provincial Education Department (18JK1199), and the Fundamental Research Funds for the Central Research Institutes (TKS170102 and TKS170108).

References

[1] Wang, L. Z., Yin, Z. Y. (2015) Stress dilatancy of natural soft clay under an undrained creep
condition. International Journal of Geomechanics., 15(5): A4014002.

[2] Cetin, H., Gokog, L. A. (2013) Soil structure changes during drained and undrained triaxial shear of a clayey soil. Soils and Foundations., 53(5):628-638.

[3] Lai, X. L., Wang, S. M., Ye, W. M. et al. (2014) Experimental investigation on the creep behavior of an unsaturated clay. Canadian Geotechnical Journal., 51(6):621-628.

[4] Chen, X. B., Zhang, J. S., Liu, B. C., et al. (2008) Effects of stress conditions on rheological properties of granular soil in large triaxial rheology laboratory tests. Journal of Central South University of Technology (English Edition), 15(1):397-401.

[5] Ma, W. B., Rao, Q. H., Li, P., et al. (2014) Shear creep parameters of simulative soil for deep-sea sediment. Journal of Central South University., 21(12):4682-4689.

[6] Wang, S. H., Qi, J. L., Yin, Z. Y., et al. (2014) A simple rheological element based creep model for frozen soils. Cold Regions Science and Technology., 106:47-54.

[7] Di, M. C., Vassallo, R., Vallario, M. (2013) Plastic and viscous shear displacements of a deep and very slow landslide in stiff clay formation. Engineering Geology., 162:53-66.

[8] Ter-Martirosyan, Z. G., Ter-Martirosyan, A. Z. (2013) Rheological properties of soil subject to shear. Soil Mechanics and Foundation Engineering., 49(6):219-226.

[9] Yin, J. H. (2015) Fundamental issues of elastic viscoplastic modeling of the time-dependent stress-strain behavior of geomaterials. International Journal of Geomechanics., 15(5): A4015002.

[10] Yin, J. H., Tong, F. (2011) Constitutive modeling of time-dependent stress-strain behaviour of saturated soils exhibiting both creep and swelling. Canadian Geotechnical Journal., 48(12): 1870-1885.

[11] Adachi, T., Oka, F. (1982) Constitutive equations for normally consolidated clay based on elasto-viscoplasticity. Soils and Foundations., 22(4):57-70.

[12] Kamei, T., Sakajo, S. (1995) Evaluation of undrained shear behaviour of K0-consolidated cohesive soils using elasto-viscoplastic model. Computers and Geotechnics., 17(3):397-417.

[13] Sun, D. A., Matsuoka, H., Yao, Y. P. et al. (2004) An anisotropic hardening elastoplastic model for clays and sands and its application to FE analysis. Computers and Geotechnics., 31(1):37-46.

[14] Yin, Z. Y., Chang, C. S., Karstunen, M., et al. (2010) An anisotropic elastic-viscoplastic model for soft clays. International Journal of Solids and Structures., 47(5):665-677.

[15] Valanis, K. C. (1980) Fundamental consequences of a new intrinsic time measure: Plasticity as a limit of the endochronic theory. Archiwum Mechaniki Stosowanej., 32(2):171-191.

[16] Daflalias, Y. F. (1986) An anisotropic critical state clay plasticity model. Mechanics Research Communications., 13(4):341-347.

[17] Kaliamkin, V. N., Daflalias, Y. F. (1990) Theoretical aspects of the elastoplastic-viscoplastic bounding surface model for cohesive soils. Soils and Foundations., 30(3):11-24.

[18] Sun, M. Q., Wang, Q., Niu, C. C., et al. (2016) Research on the one-dimensional rheological consolidation theory that considers secondary consolidation effect. Journal of Computational and Theoretical Nanoscience., 13(2):1136-1146.

[19] Brandes, H. G., Sadd, M. H., Silva, A. J. (1996) Finite element modelling of a deep sea clay in long-term laboratory creep tests. International Journal for Numerical and Analytical Methods in Geomechanics., 20(12): 887-905.

[20] Gao, H. M., Chen, Y. M., Liu, H. L. et al. (2012) Creep behavior of EPS composite soil. Science China Technological Sciences., 55(11):3070-3080.

[21] Sun, M. Q., Wang, Q., Ruan, Y. K., et al. (2015) Settlement prediction of soft soil foundation based on consolidation and creep theory. International Journal of Simulation: Systems, Science and Technology., 16(2):21-28.

[22] Zhu, Y. B., Yu, H. M. (2014) An improved Mesri creep model for unsaturated weak intercalated soils. Journal of Central South University., 21(12):4677-4681.

[23] Wang, Z. C., Wong, R. C. K. (2016) Strain-dependent and stress-dependent creep model for a till subject to triaxial compression. International Journal of Geomechanics., 16(3): 04015084.
[24] Zhu, Y. B., Yu, H. M. (2014) An improved Mesri creep model for unsaturated weak intercalated soils. Journal of Central South University., 21(12):4677-4681.

[25] Li, D. W., Fan, J. H., Wang, R. H. (2011) Research on visco-elastic-plastic creep model of artificially frozen soil under high confining pressures. Cold Regions Sciences and Technology., 65(2): 219-225.

[26] Zhu, H. H., Zhang, C. C., Mei, G. X. (2016) Prediction of one-dimensional compression behavior of Nansha clay using fractional derivatives. Marine Georesources & Geotechnology., 1-10.

[27] Liu, Y. K., Deng, Z. B., Cao, P., et al. (2012) Triaxial creep test and modified Singh-Mitchell creep model of soft clay. Journal of Central South University (Science and Technology)., 43(4): 1440-1446.

[28] Wang, Y. Z., Huang, D. X., Xiao, Z. (2012) Experimental research on creep properties of two typical soft clays in coastal region of Tianjin. Chinese Journal of Geotechnical Engineering., 34(2): 379-384.