

## Research Article

# Creep Behavior of Saturated Clay in Triaxial Test and a Hyperbolic Model

Bin Xiao <sup>1,2</sup>, Minyun Hu <sup>1</sup>, Peijiao Zhou <sup>3</sup>, Yuke Lu <sup>1</sup> and Yong Zhang <sup>1</sup>

<sup>1</sup>Department of Civil Engineering, Zhejiang University of Technology, Hangzhou, China 310014

<sup>2</sup>Zhejiang Tongji Science and Technology Vocational College, Hangzhou, China 311231

<sup>3</sup>Zhejiang College of Construction, Hangzhou, China 311231

Correspondence should be addressed to Minyun Hu; huminyun@zjut.edu.cn

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As one of the basic mechanical properties of soil, the creep property of a given type soil is related to stress path, and stress level. In this paper, triaxial shear creep tests under different deviatoric stress levels were performed on both intact sample and the reconstituted sample of clay taken from Hangzhou, China. Based on the Boltzmann linear superposition principle, the creep curves of the clay sample under different levels of deviatoric stress were obtained, and the creep characteristics of the intact sample and the reconstituted sample were compared in both total stress creep analysis and effective stress creep analysis. Furthermore, the creep curves were fitted using a hyperbolic creep model. The results show that (1) under the same stress level, the creep of intact sample evolves more than that of reconstituted sample; (2) the hyperbolic creep model is suited to describe the creep characteristics of intact and reconstituted clay, and the model parameters  $A_s$  and  $B_s$  can be linearly correlated to the stress level  $D_r$ ; (3) for the application of the hyperbolic model, the total stress analysis works better, and the model parameters  $A_s$  and  $B_s$  can be determined by a linear relationship with  $D_r$ .

## 1. Introduction

Creep is a macroscopic reflection of time effect of soil's deformation due to stress change. It can lead to long-term settlement of building foundation and road embankment, which may cause adverse impact on the serviceability of buildings and the maintenance of highways. As compared to sandy soils, the creep of clayey soils is considerable and cannot be neglected, so it is essential to investigate the creep characteristics of saturated clays.

Previous experimental studies [1–5] have shown that the creep character of soil depends on soil's structure and is affected by its sedimentation history and deposition environment. Moreover, the loading path and stress level also affect the soil creep characteristics [6, 7]. For example, in one-dimensional (1-D) compression and consolidation test, a soil sample creeps in one dimension and the creep will be affected by soil's stiffness and the stress level [8, 9]. However, in triaxial test, a soil sample may deform in three directions,

and the induced volume change and excess pore pressure dissipation are associated to the drainage condition [5, 10], so the creep characteristics are loading path dependent.

To predict the deformation process of soil ground under an applied loading, it is necessary to establish creep model which is suitable for various stress conditions. Based on the 1-D compression creep test of Hong Kong marine reconstituted clay, Yin [11] proposed a nonlinear creep model with logarithmic time as a variable. By carrying out triaxial creep tests of soils under different stress levels, Singh and Mitchell [12] put forward a Singh-Mitchell empirical stress creep model, in which the exponential function is used to describe the relationship between stress and strain, and the power function is used to describe the relationship between strain and time. However, the model performs poorly when the deviatoric stress level is lower than 20% or higher than 80%. Mesri et al. [13] proposed creep model using two nonlinear functions to describe the stress-strain and strain-time relationship, respectively. Lu et al. [14] conducted a series of

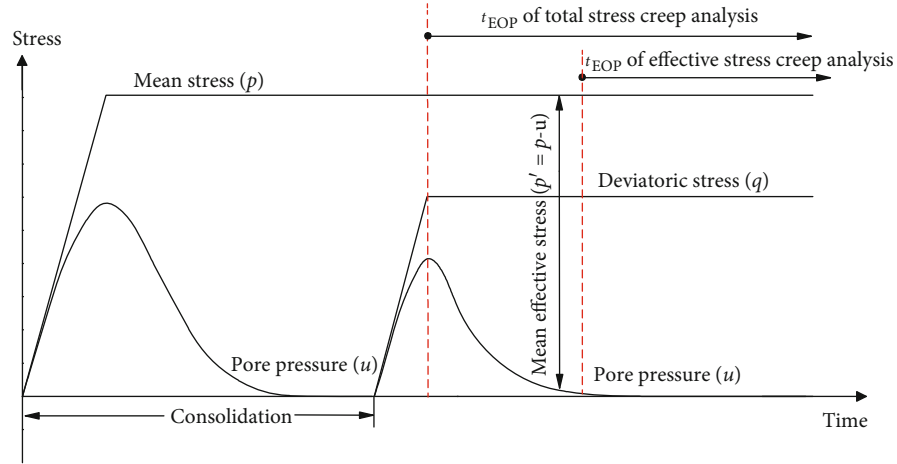


FIGURE 1: Total stress creep and effective stress creep.

TABLE 1: Physical index of soil samples.

Soil type	Depth (m)	Specific Gravity Gs	Water content w(%)	Void ratio $e_0$	Liquid limit wL (%)	Plastic limit wP (%)	Density ( $g/cm^3$ )
Intact clay	20-25	2.74	31.1	0.892	39.20	22.00	1.898
Reconstituted clay			28				1.854

triaxial consolidation undrained creep tests on Hunan road-bed soft soil and proposed an undrained creep formula. Based on the experiments of the triaxial shear creep test on reconstituted clays and by comparing different creep models, Xiao [15] proposed a hyperbolic creep model by considering the drainage condition.

In order to discuss the creep characteristics of clay, it is necessary to clarify the relationship between consolidation and creep of clay. There are two viewpoints: one point assumes that the creep and the consolidation deformation of clay are coupled and occur simultaneously; another point assumes that there is no creep occurrence during consolidation process, i.e., creep happens after consolidation. In the triaxial shear test, the total mean stress  $p((\sigma_1 + 2\sigma_3)/3)$  is taken by the soil skeleton and pore water, while the deviatoric stress  $q(\sigma_1 - \sigma_3)$  is taken only by the soil skeleton. Therefore, there are two methods for deviatoric strain creep analysis according to the two points, respectively: the first one is the total stress creep (TSC) analysis, in which the time when the total mean stress and the deviatoric stress remains unchanged is set as the starting point of creep; the second one is the effective stress creep (ESC) analysis, in which the time, when the effective mean stress and the deviatoric stress remain unchanged, is set as the starting point of creep, as shown in Figure 1.

From the above analysis, in order to investigate the creep characteristics of specific clay and to establish an applicable creep model, it is necessary to carry out laboratory experiments simulating real loading process. In this paper, triaxial shear creep tests were carried out on the intact sample and the reconstituted sample of a saturated clay, respectively, taken from Hangzhou Bay area, China. Total stress creep analysis and effective stress creep analysis were applied to study the creep characteristics of intact clay and reconsti-

TABLE 2: Triaxial creep test plan.

Soil type	Shear strength in CU test ( $q_f/kPa$ )	Loading steps ( $q/kPa$ )
Intact clay	430	60-120-180-240-300-360-420
Reconstituted clay	330	60-120-180-240-300

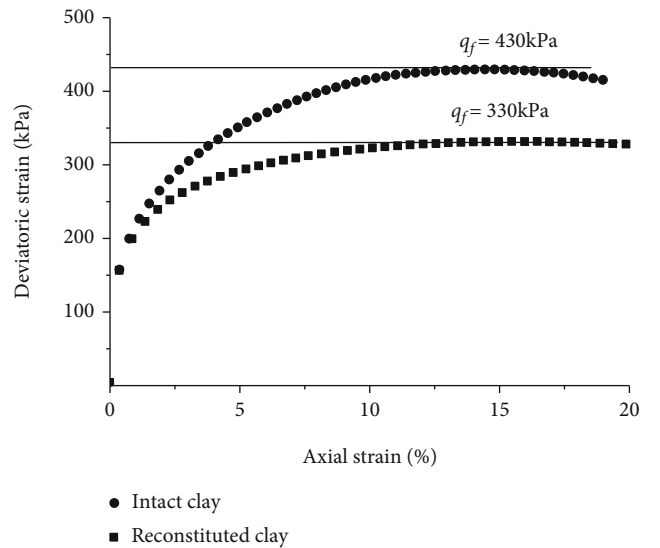


FIGURE 2: Triaxial consolidation undrained (CU) test.

tuted clay under different stress levels. Then, an empirical creep model of saturated clay was proposed for use in practice.

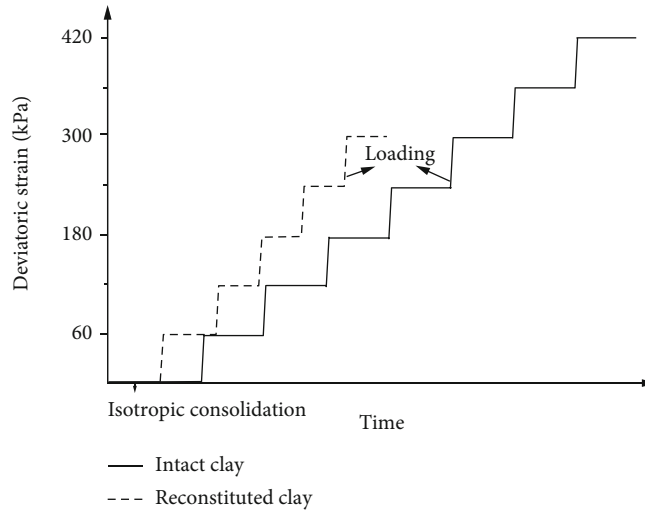


FIGURE 3: Stress path of creep test.

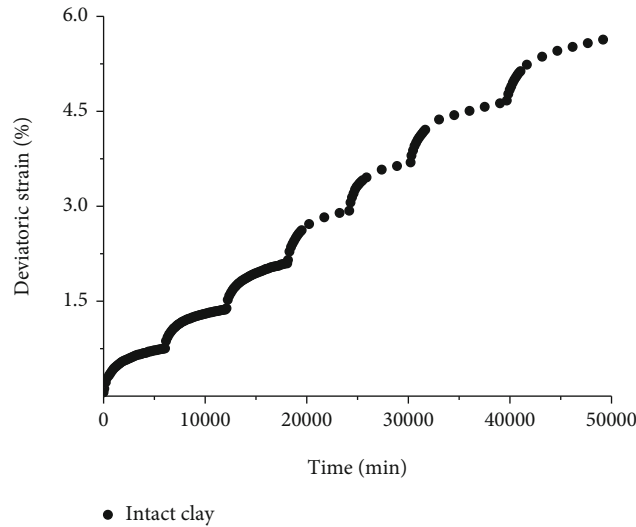


FIGURE 4: Whole process curve of the triaxial deviatoric strain of intact soil.

## 2. Soil Sample Preparation and Test Plan

**2.1. Soil Sample Preparation.** The soil sample was taken from a depth of 20-25 m below the surface of an engineering site in Hangzhou, China, and was judged to be saturated clay. The physical index is shown in Table 1. The intact sample was obtained using the soil drilling extractor; the original structure was maintained during sample preparation. The reconstituted clay sample was made by compacting the soil with a water content of 28%, layer by layer into the sample preparation mould, and its dry density was the same as the intact clay soil. The dimension of the cylindrical sample used in the triaxial test is  $H \times D = 76 \times 38$  mm. The room temperature was controlled to be  $24 \pm 1^\circ\text{C}$  during the test.

**2.2. Test Method.** In this test, the GDS triaxial apparatus was adopted, by which the resolution of strain measurement can reach  $10^{-5}$ . After the soil sample was saturated to be 95%, it

was then isotropically consolidated under the pressure of  $p' = 400$  kPa. After the consolidation, the deviatoric stress was increased in steps to the prescribed levels under drained condition. The strain development was monitored under different levels of deviatoric stress.

To examine the effect of soil's structure on creep characteristics, the intact and the reconstituted soil sample were both tested by the same procedures but with different loading steps, as shown in Table 2. Under consolidated undrained shearing the strength  $q_f$  of intact sample and reconstituted clay were 430 kPa and 330 kPa, respectively, as shown in Figure 2. The loading scheme was designed accordingly (as shown in Table 2). The time process of loading for two samples are shown in Figure 3. The loading time for each level of deviatoric stress was adjusted according to the pore pressure dissipation to ensure development of secondary consolidation. For each loading step, the stress state retained until the axial strain rate is less than  $0.0001/\text{d}$  in secondary consolidation process.

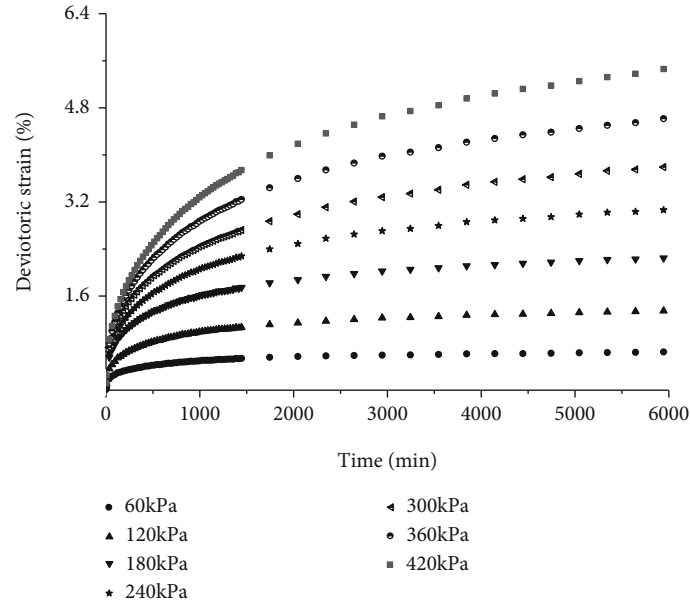


FIGURE 5: Deviatoric strain creep curve of intact soil.

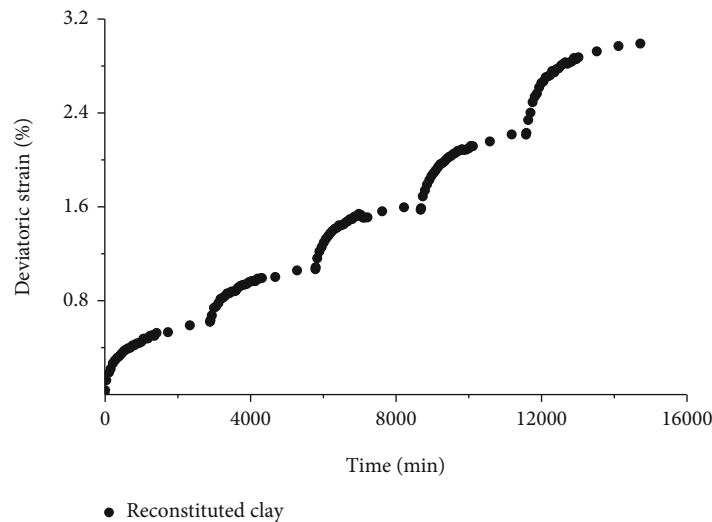


FIGURE 6: Whole process curve of triaxial deviatoric strain evolution of reconstituted soil.

### 3. Test Results and Analysis

#### 3.1. Total Stress Creep Analysis

- (1) While analysing the total stress creep of the intact sample, the shear creep test is divided into 7 levels. As shown in Figure 4, under each level of deviatoric stress, the deviatoric strain of the intact sample showed a nonlinear variation with time. As the deviatoric stress increased, the strain increment over time also increased

By superimposing the test curves using Boltzmann's linear superposition principle [3], the strain-time curve of the intact sample under each deviatoric stress can be obtained and shown in Figure 5. It can be seen that as the deviatoric

stress level was increased, the deviatoric strain creep evolves more and in a longer time.

- (2) While analysing the total stress creep of the reconstituted sample, the shear creep was divided into 5 levels. As shown in Figure 6, the deviatoric strain rate of the reconstituted sample also exhibited non-linear attenuation characteristics; with the increase of the stress level, the increment of strain obviously increased. By applying the Boltzmann linear superposition principle, the total stress creep curves of the reconstituted sample under different deviatoric stresses is shown in Figure 7. It can be seen that the greater the deviatoric stress, the greater the deviatoric strain creep evolution, and the longer it takes the creep to become stable

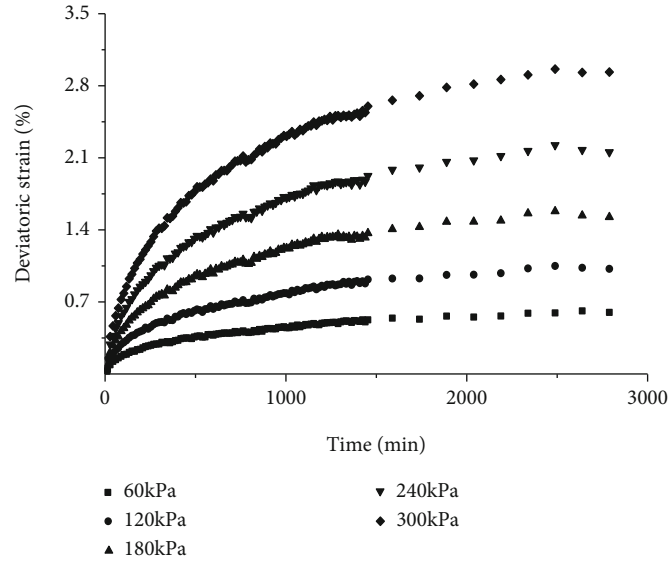


FIGURE 7: Deviatoric strain creep curve of reconstituted soil.

By comparing the whole curves of the deviatoric strain (Figures 4 and 6) and the creep curves (Figures 5 and 7) under different deviatoric stresses, it can be found that both intact clay and reconstituted clay samples exhibit similar creep characteristics. However, for the same deviatoric stress level, the creep of intact clay sample gave a larger strain evolution than reconstituted sample, and a shorter time to be stabilized in creep process.

3.2. Effective Stress Creep Analysis

- (1) There are two methods of dividing primary and secondary consolidation: one method is based on pore pressure dissipation analysis, where the cut off time can be determined when consolidation degree reaches 95%, which is also known as the starting time of effective stress creep; the other method is based on  $e-p$  curve analysis, where  $t_{EOP}$  can be determined according to the curvature change in  $e-\log p$  curve [20, 21], as shown in Figure 8,  $t_{EOP}$  was determined by pore pressure- $\log t$  curve.

Tables 3 and 4 show the division results of the intact sample and the reconstituted sample, respectively, by both methods. It can be found that

- (i) For intact and reconstituted samples, the  $t_{EOP}$  determined by the curve analysis method was shorter than that of the pore pressure dissipation method, and the corresponding consolidation degree of the intact sample and the reconstituted sample  $t_{EOP}$  was averaged about 80% and 70%, respectively. Considering that the permeability coefficient of the sample will change during consolidation and the primary and secondary consolidations will be coupled to some extent, the curve characteristic method is acceptable and then applied to later analysis

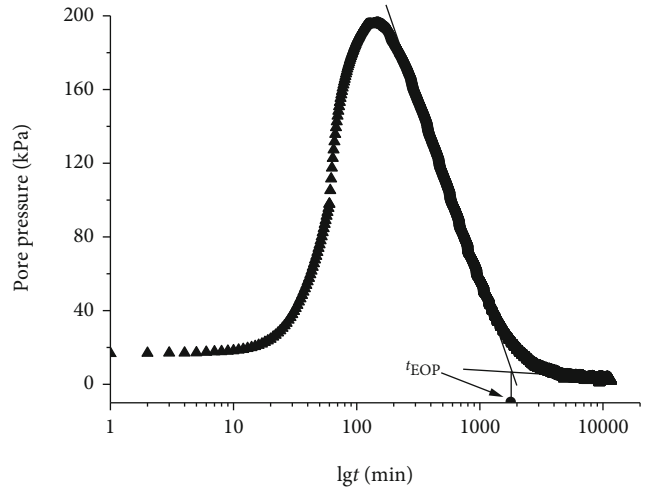


FIGURE 8: Curve analysis method to determine  $t_{EOP}$ .

- (ii) In both division method analysis, the starting time of secondary consolidation of the intact sample seems later than that of the reconstituted sample, indicating the impact of soil's initial structure
- (iii) The higher the deviatoric stress level, the later the starting time of the secondary consolidation

Based on the above analysis, the curve analysis method was suggested to determine the effective stress creep starting point of saturated clay.

- (2) Effective stress and creep analysis. Figures 9 and 10 show the deviatoric strain and creep curves of intact sample and reconstituted sample using the curve analysis method, respectively. It can be found that 1) for intact sample and reconstituted sample, the higher the deviatoric stress level, the more the creep evolution and the higher the creep rate; 2) in the

TABLE 3:  $t_{EOP}$  value and pore pressure dissipation degree  $(u_0 - u)/u_0 \times 100\%$  of intact samples.

Soil type	Deviatoric stress (kPa)	Curve analysis method		Pore pressure dissipation method	
		$t_{EOP}$ (min)	$(u_0 - u)/u_0 \times 100\%$	$t_{EOP}$ (min)	$(u_0 - u)/u_0 \times 100\%$
Intact samples	60	1335	73.90	2778	95
	120	2028	77.20	3250	95
	180	2186	81.60	3763	95
	240	2816	83.47	3914	95
	300	2839	86.09	4215	95
	360	3714	87.74	4333	95
	420	4078	86.73	4747	95

Note:  $u_0$  represents the maximum pore pressure and  $u$  is the corresponding pore pressure at  $t_{EOP}$ .

TABLE 4:  $t_{EOP}$  value and pore pressure dissipation degree  $(u_0 - u)/u_0 \times 100\%$  of reconstituted samples.

Soil type	Deviatoric stress (kPa)	Curve analysis method		Pore pressure dissipation method	
		$t_{EOP}$ (min)	$(u_0 - u)/u_0 \times 100\%$	$t_{EOP}$ (min)	$(u_0 - u)/u_0 \times 100\%$
Reconstituted samples	60	682	72.97	1793	95
	120	903	69.12	2018	95
	180	1080	63.48	2158	95
	240	1289	65.96	2501	95
	300	1286	64.71	2661	95

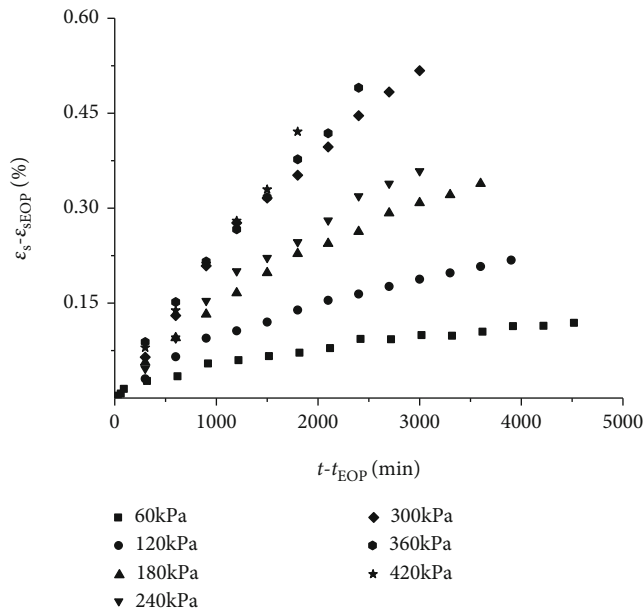


FIGURE 9: Deviatoric strain creep curve of the intact sample.

secondary consolidation stage, the development of the deviatoric strain of intact sample differs from that of the reconstituted sample

#### 4. Creep Model and Parameter Analysis of Saturated Clay

4.1. *Establishment of Hyperbolic Creep Model.* Based on theory, experience, quasitheoretical, and quasiexperience, researchers proposed creep models suitable for different types of soils [11–20]. In this paper, two models (Yin's

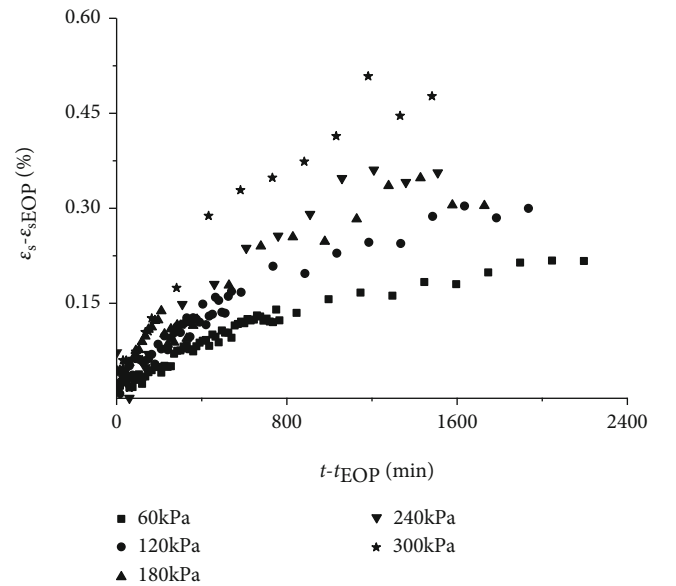


FIGURE 10: Deviatoric strain creep curve of reconstituted soil.

model [11] and Singh-Mitchell model [12]) commonly used to describe the creep characteristics of soft clay were selected to fit the creep curves of intact soil. As shown in Figure 11, when the stress level is low, both models can be used to fit the creep curve of intact samples. However, when the stress level is high, the fitting accuracy of Singh-Mitchell model becomes low, while Yin's model cannot apply. The application of the two models to creep curves of intact soil seems not satisfactory.

Based on test results, the hyperbolic creep model proposed by Xiao [15] was used to fit the creep characteristics of the intact and reconstituted sample, as follows:

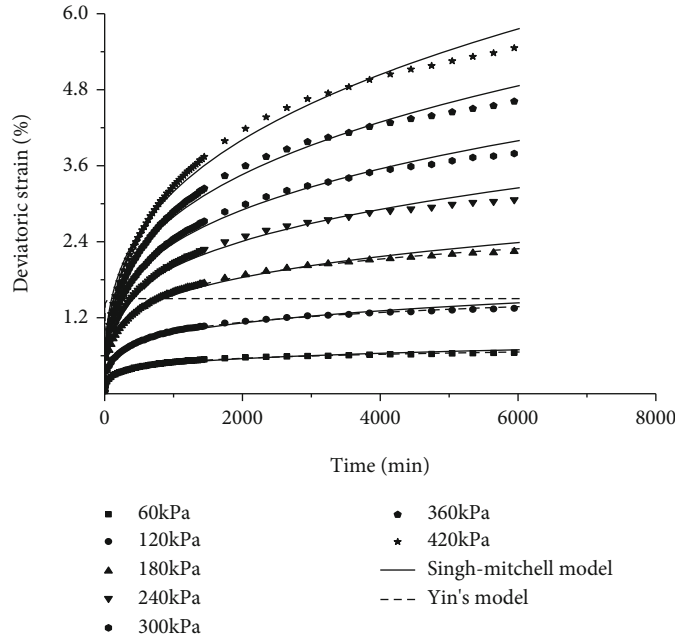


FIGURE 11: Fitting curves of intact soil by the Singh-Mitchell model and Yin's model.

$$\varepsilon_s(t) - \varepsilon_s(t_0) = A_s \frac{t - t_0}{B_s + (t - t_0)}, \quad (1)$$

where  $\varepsilon_s(t)$  represents the deviatoric strain of the sample at time  $t$ ;  $\varepsilon_s(t_0)$  represents the deviatoric strain of the sample at a time  $t_0$ ;  $t_0$  is the reference time;  $A_s$  is the final deviatoric strain of creep; when  $t \rightarrow \infty$ ,  $A_s = \varepsilon_s(\infty) - \varepsilon_s(t_0)$ ; and  $B_s$  is the characteristic time of creep of a soil, which is the time when the creep reaches 50% of the total creep.

#### 4.2. Fitting Analysis of Total Stress Creep

- (1) Based on the triaxial test results of the intact sample, the creep curves of the intact sample under multiple deviatoric stress levels were fitted using the hyperbolic empirical model, as shown in Figure 12. It can be found that the hyperbolic creep model can fit well the total stress creep process of the intact sample. Table 5 gives the parameters of hyperbolic model by fitting intact clay sample under different deviatoric stresses, and shows the accuracy of the model is highly satisfying. As the stress level  $D_r = (\sigma_1 - \sigma_3)/(\sigma_1 - \sigma_3)_f$  increases, and fitting parameters  $A_s$  and  $B_s$  are positively correlated with the stress level
- (2) The creep curves of the reconstituted sample under multiple deviatoric stress levels were fitted using the hyperbolic empirical model and shown in Figure 13. According to the fitting analysis given in Table 6, it can be seen that the fitting accuracy is also satisfactory. As the stress level increases,  $A_s$  and  $B_s$  increase as well, exhibiting similar correlation between model parameters and stress level to the intact sample

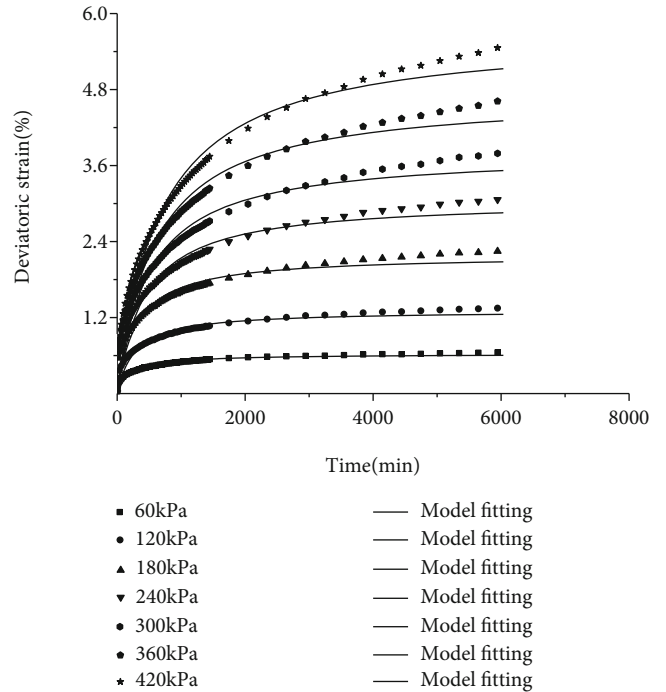


FIGURE 12: Fitting curves of total stress creep curve of intact soil.

- (3) Based on the model fitting results given in Tables 5 and 6, Figure 14 shows the relationship between the model parameters  $A_s$  and  $D_r$ . It can be seen that for both intact sample and reconstituted sample, the final deviatoric strain creep  $A_s$  increases with the deviatoric stress level; Under the same stress level, the final deviatoric strain creep of the intact sample

TABLE 5: Hyperbolic model parameters and correlation coefficient  $R^2$  of triaxial creep test (intact clay).

Deviatoric stress(kPa)	Deviatoric stress level $D_r$	$A_s$ (%)	$B_s$ (min)	Correlation coefficient $R^2$ (%)
60	0.14	0.63	215.82	96.76
120	0.28	1.31	278.18	96.39
180	0.42	2.20	307.76	96.39
240	0.56	3.06	426.34	96.79
300	0.70	3.81	497.59	96.68
360	0.84	4.72	578.34	97.19
420	0.98	5.70	674.58	97.57

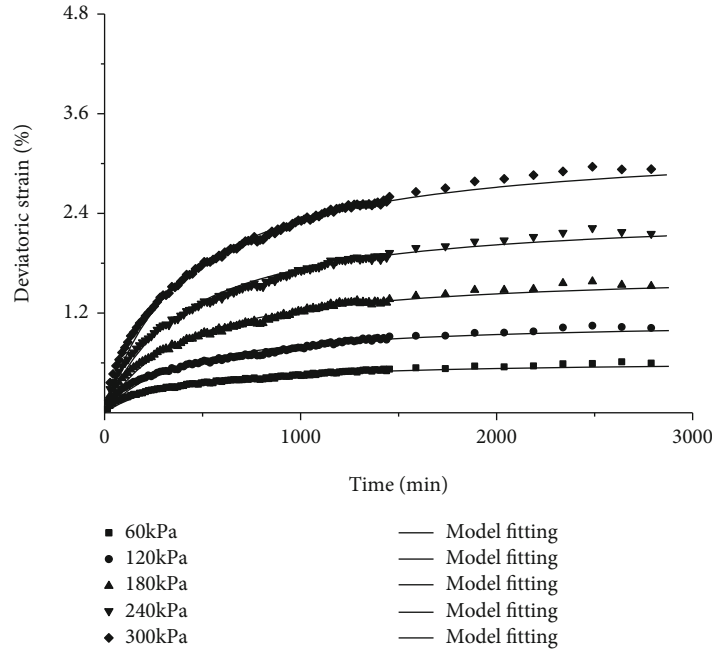


FIGURE 13: Fitting curves of total stress creep curve of reconstituted soil.

TABLE 6: Hyperbolic model parameters and correlation coefficient  $R^2$  of triaxial creep test (reconstituted clay).

Deviatoric stress(kPa)	Deviatoric stress level $D_r$	$A_s$ (%)	$B_s$ (min)	Correlation coefficient $R^2$ (%)
60	0.18	0.63	367.21	97.77
120	0.36	1.12	379.50	98.08
180	0.55	1.71	388.81	98.90
240	0.73	2.43	404.11	99.14
300	0.91	3.28	416.40	99.39

was greater than that of the reconstituted sample. Figure 15 shows the relationship between the model parameters  $B_s$  and  $D_r$ . It can be found that  $B_s$  increased with stress level  $D_r$  for intact clay, while  $B_s$  of reconstituted clay changes over a narrow range with stress level increased between 0~1. On average,  $B_s$  is about 400 min

It can be seen from Figures 14 and 15 that the model parameters,  $A_s$  and  $B_s$ , of both the intact sample and the reconstituted sample are in a linear correlation with the

stress level  $D_r$ . The linear fitting relationship is given in equations (2)–(5).

$$\text{Intact clay : } A_s = 5.6 * D_r, \quad (2)$$

$$\text{Intact clay : } B_s = 554.51 * D_r + 116.02, \quad (3)$$

$$\text{Reconstituted clay : } A_s = 3.41 * D_r, \quad (4)$$



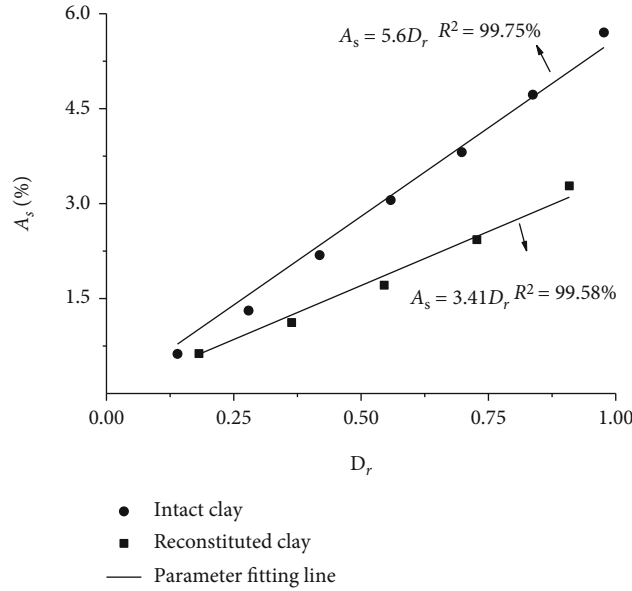


FIGURE 14: Model parameter  $A_s$  versus deviatoric stress level  $D_r$ .

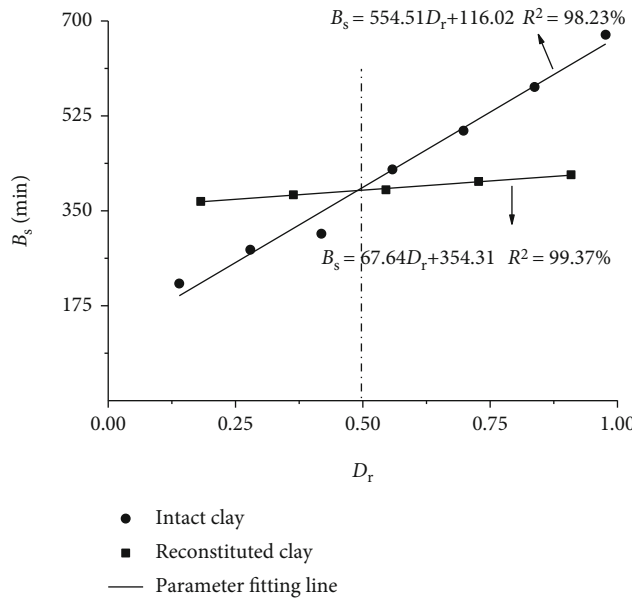


FIGURE 15: Model parameter  $B_s$  versus deviatoric stress level  $D_r$ .

Reconstituted clay :  $B_s = 67.64 * D_r + 354.31$ . (5)

4.3. Fitting Analysis of Effective Stress Creep

(1) According to the fitted effective stress creep curves of the intact sample under different stress levels using the hyperbolic creep model (Figure 16), model parameters are extracted into Table 7. The fitting accuracy is higher than 99%. The parameters  $A_s$  and  $B_s$  of the intact sample increases with the stress level. It needs to be noticed that when the deviatoric stress level  $D_r$  reached 98%, although the accuracy of the hyperbolic model fitting was still very good, the creep parameters  $A_s$  and  $B_s$  of the intact sample were

greatly increased, suggesting that when the deviatoric stress is close to the failure value, the shear creep of the soil sample will increase and the creep development will not be stable for a long time. In engineering practice, under such a high-stress level, the failure problem needs to be focused on rather than the deformation problem. This phenomenon was not observed in total stress creep, though parameter  $A_s$  was increased rapidly under higher stress level

(2) Figure 17 shows the fitting results of the effective stress creep curves of the reconstituted sample under

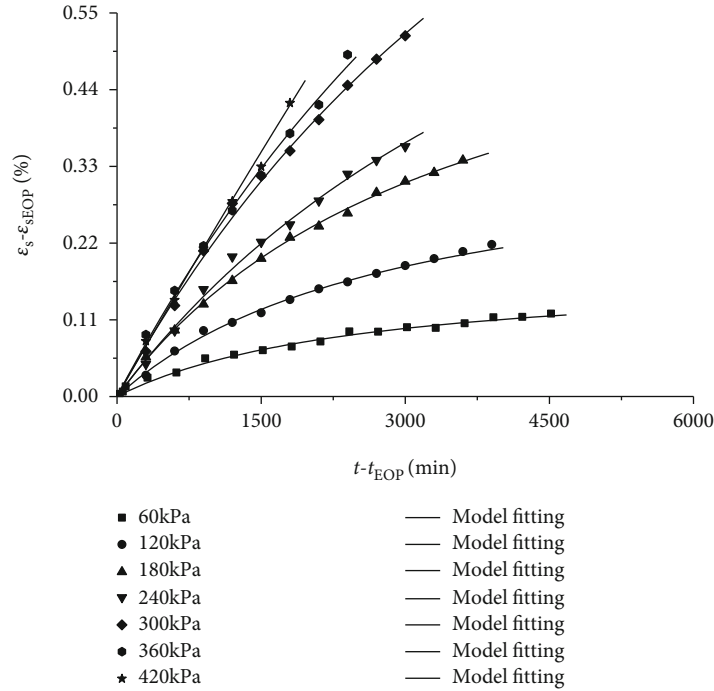


FIGURE 16: Fitting curves of effective stress creep curve of intact soil.

TABLE 7: Hyperbolic model parameters(kPa) and correlation coefficient  $R^2$  of the triaxial creep test (intact clay).

Deviatoric stress(kPa)	Deviatoric stress level $D_r$	$A_s$ (%)	$B_s$ (min)	Correlation coefficient $R^2$ (%)
60	0.14	0.18	2575	99.14
120	0.28	0.37	2936	99.05
180	0.42	0.67	3556	99.76
240	0.53	1.07	5787	99.71
300	0.70	1.65	6521	99.55
360	0.84	1.88	7126	99.35
420	0.98	10.22	42239	99.72

different stress levels. Model parameters were extracted and given in Table 8. It shows that the fitting accuracy is higher than 90%, and with the increase of stress level, the value of  $B_s$  change very little over the stress level rang of 0~1

- (3) According to the model parameters given in Tables 7 and 8, Figure 18 shows the relationship between  $A_s$  and  $D_r$  (omitting the creep data of high-stress level of  $D_r = 98\%$ ). It can be seen that the model parameters  $A_s$  and  $D_r$  are in positive correlation. Figure 19 shows the relationship between the model parameters  $B_s$  and  $D_r$ . For intact clay, the linear relationship is broken at  $D_r = 0.5$ . In both sides of  $D_r < 0.5$  and  $D_r > 0.5$ , the  $B_s$  value is linearly increased with the stress level  $D_r$ . The  $B_s$  of the reconstituted sample is on an average of 1050 min for the reconstituted sample

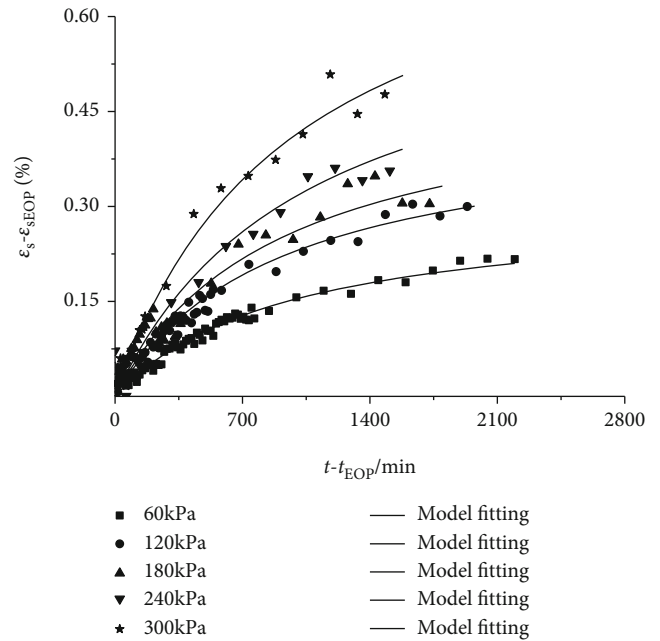


FIGURE 17: Fitting curves of effective stress creep curve of reconstituted soil.

## 5. Conclusion

The creep characteristics of the intact and reconstituted samples under different stress levels were studied through indoor triaxial shear creep tests. A hyperbolic creep model was used to fit the creep curves, and the values of model parameters were discussed. The main conclusions are as follows:

TABLE 8: Hyperbolic model parameters and correlation coefficient  $R^2$  of the triaxial creep test (reconstituted clay).

Deviatoric stress(kPa)	Deviatoric stress level $D_r$	$A_s$ (%)	$B_s$ (min)	Correlation coefficient $R^2$ (%)
60	0.18	0.30	949.72	97.36
120	0.36	0.44	891.90	97.48
180	0.55	0.50	909.39	90.36
240	0.73	0.65	1353.53	96.93
300	0.91	0.82	976.00	97.97

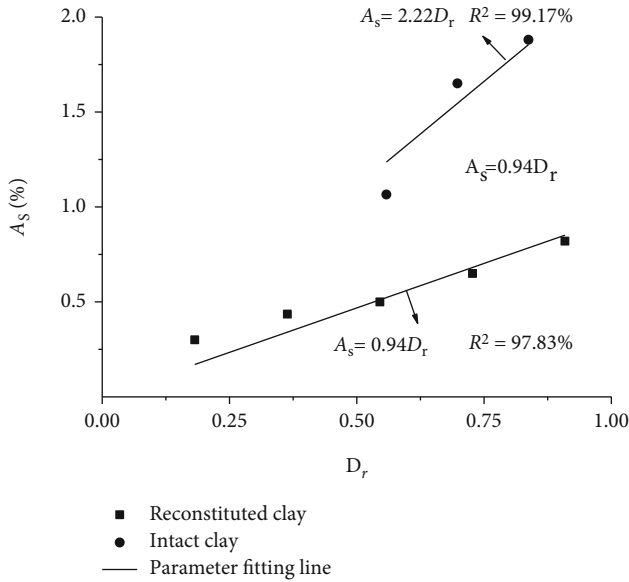


FIGURE 18: Model parameter  $A_s$  versus deviatoric stress level  $D_r$ .

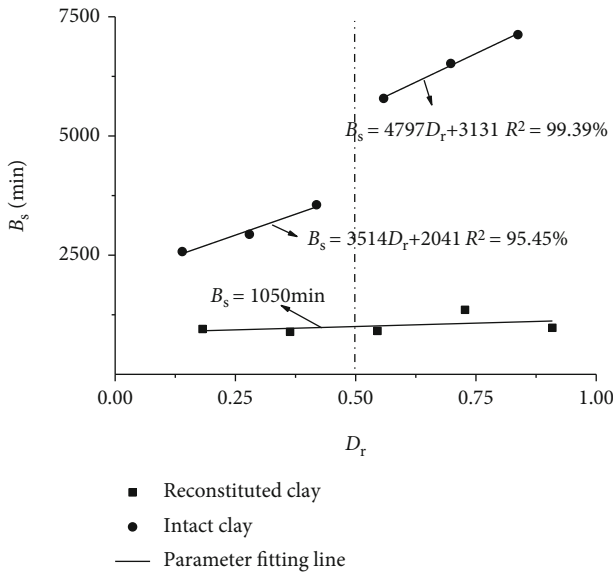


FIGURE 19: Model parameter  $B_s$  versus deviatoric stress level  $D_r$ .

(1) The creep behaviour of the studied clay under triaxial shear stress, in both intact sample and reconstituted sample, shows nonlinear variation feature;

The amount of creep and the time of creep both increase with stress level. Under the same stress state, the creep of reconstituted sample develops less than that of the intact sample, indicating that, for practical use, the creep parameters should be tested on intact samples which contain the original soil structure

- (2) The hyperbolic creep model is suitable for describing the creep behaviour of the saturated clay either in intact or in reconstituted condition. For both total stress creep analysis and effective stress creep analysis, the model fit well, indicating that the hyperbolic creep model is adaptive. The model parameters  $A_s$  and  $B_s$  both show a linear correlation with the stress level  $D_r$ . Under the same stress level, the final triaxial creep strain  $A_s$ . However, while  $B_s$  of the intact sample increases with stress level,  $B_s$  of the reconstituted sample changes very little and can be treated as a constant for a given clay
- (3) While using the total stress creep analysis, both  $A_s$  and  $B_s$  of the hyperbolic model show better linear correlation with the stress level  $D_r$  and the total stress creep analysis can be a potential recommendation for engineering application.

### Data Availability

All data generated during the study.

### Conflicts of Interest

The author declares no conflict of interests related to this article.

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