



## Creep model for unsaturated soils in sliding zone of Qianjiangping landslide<sup>☆</sup>

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### ABSTRACT

The mechanical behavior of sliding zone soils plays a significant role in landslide. In general, the sliding zone soils are basically in unsaturated state due to rainfall infiltration and reservoir water level fluctuation. Meanwhile, a large number of examples show that the deformation processes of landslides always take a long period of time, indicating that landslides exhibit a time-dependent property. Therefore, the deformation of unsaturated soils of landslide involves creep behaviors. In this paper, the Burgers creep model for unsaturated soils under triaxial stress state is considered based on the unsaturated soil mechanics. Then, by curve fitting using the least squares method, creep parameters in different matric suction states are obtained based on the creep test data of unsaturated soils in the sliding zones of Qianjiangping landslide. Results show that the predicted results are in good agreement with the experimental data. Finally, to further explore the creep characteristics of the unsaturated soils in sliding zones, the relationships between parameters of the model and matric suction are analyzed and a revised Burgers creep model is developed correspondingly. Simulations on another group of test data are performed by using the modified Burgers creep model and reasonable results are observed.

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### 1. Introduction

Landslide is a major geological disaster, which poses a great threat to human life and property in most parts of the world (Yang and Lu, 1993). Sliding zone, one of the significant structural elements of a landslide, records the detailed information for physical changes and dynamic developments in the evolution process of a landslide. In terms of sliding belt formed in the development of a landslide, the creep behaviors of the soils in sliding zone can reveal the mechanism of landslide formation, and serves as an important index for the prediction and evaluation of a landslide (He, 2005). On the one hand, soils in sliding zone are basically unsaturated due to rainfall infiltration or water level fluctuation of reservoir (Riemer, 1992; Furuya et al., 1999; Wang et al., 2008); on the other hand, a large number of cases show that the deformation of landslides always takes a long period of time, which means that time-dependent properties of landslide soils are observed. According to this understanding,

a series of triaxial creep tests on unsaturated sliding zone soils were performed (Lai, 2010; Lai et al., 2010). To investigate and describe the creep behaviors of the unsaturated soils, an appropriate creep model needs to be constructed on the basis of creep test data.

At present, creep models for the saturated soils can be roughly classified into four categories: component model, integration model, empirical model and semi-empirical model. Among these models, component model, which is constructed on the basis of linear visco-elastoplastic theorem, is featured with clear physical meaning, visual concept and good reflection of rheological properties of geotechnical materials (Sun, 1999). For this purpose, numerous researches have been conducted using component models (Liingaard et al., 2004; Wang et al., 2004; Sun, 2007; Yan et al., 2008; Dey and Basudhar, 2010; Zhang et al., 2012). Most of above-mentioned researches using creep models took the saturation condition into consideration, but the unsaturated condition was rarely considered.

In this paper, a revised Burgers creep model for unsaturated soils in triaxial stress state is constructed. Then, all the parameters are obtained by the self-developed FSR-6 unsaturated triaxial creep apparatus. Finally, the relationships between parameters of the model and matric suction are analyzed.

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**Table 1**  
Physico-mechanical parameters of soils in the sliding zone of Qianjiangping landslide (Chen, 2005; Lai, 2010).

Specific gravity	Water content (%)	Density (g/cm <sup>3</sup> )	Liquid limit (%)	Plastic limit (%)	Cohesion (kPa)	Internal friction angle (°)
2.71	19	2.02	40.5	17	28.3	18

## 2. Creep test and results

### 2.1. Soil samples

The soils used in laboratory test were sampled from the sliding zone of Qianjiangping landslide, which is located at the south bank of Qinggan River, a branch of Yangtze River in Zigui County, Yichang, China. In this test, the sliding zone soils with particle size less than 2 mm were used to make remolded samples for laboratory test, because it is very difficult to obtain field undisturbed soil samples from the sliding zone of landslides.

Some basic laboratory indices of soils in the sliding zone of Qianjiangping landslide (Chen, 2005; Lai, 2010) are summarized in Table 1.

### 2.2. Creep test apparatus

The FSR-6 unsaturated triaxial creep apparatus has been developed based on conventional triaxial creep apparatus and unsaturated triaxial apparatus. It consists of loading system and air pressure controlling system (Guan and Wang, 2008). Hence, it is capable of applying constant shear stress and constant air pressure. The FSR-6 unsaturated triaxial creep apparatus is composed of several parts, including confining pressure controlling system, matric suction controlling system, pore water pressure measuring system, axial loading system, cell pressure chamber, measurement and data acquisition system (see Fig. 1).

The axial load was exerted in a conventional way by applying deadweights in the axial direction. The dimensions of the soil specimens are 120 mm in length and 60 mm in diameter.

### 2.3. Test scheme

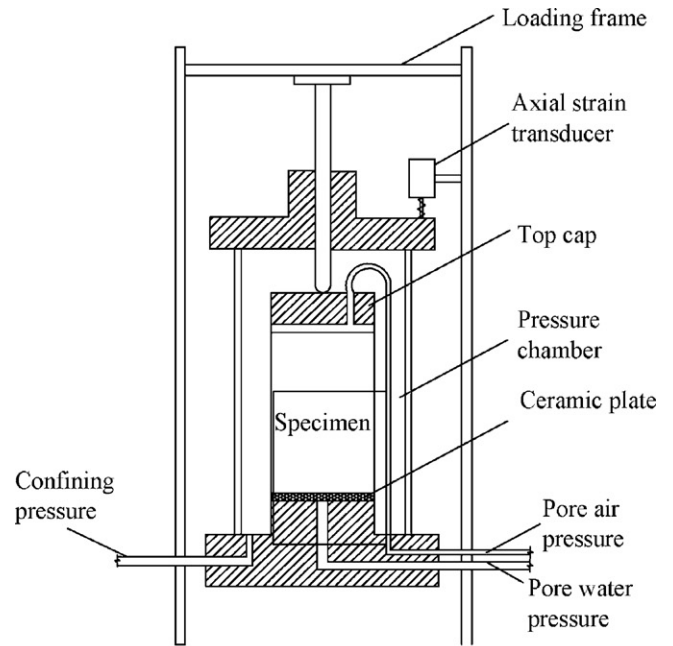
The scheme of creep test is listed in Table 2. In order to investigate the effect of matric suction on soil creep characteristics under the unsaturated condition, the net confining pressure  $\sigma'_3 (= \sigma_3 - u_a)$  was kept at 100 kPa, and the deviator stress level (the ratio of the deviator stress,  $q$ , to the drained shear strength,  $q_f$ ) was kept at 0.55. The matric suction,  $s$ , was controlled at 50–250 kPa by adjusting the pore air pressure  $u_a$ . Five groups of drained triaxial creep tests have been conducted considering drainage condition of landslide in a long period of time.

### 2.4. Creep test results

According to the test scheme shown in Table 2, each group of test was performed within about one week. The creep test results are shown in Fig. 2, in which simulated curves were obtained using extended Burgers creep model (see Section 3.2).

**Table 2**  
Scheme of creep test.

Group	$\sigma'_3$ (kPa)	$s$ (kPa)	$q_f$ (kPa)	$q$ (kPa)	$q/q_f$
1	100	50	187	103	0.55
2	100	100	225	124	0.55
3	100	150	256	141	0.55
4	100	200	341	188	0.55
5	100	250	347	191	0.55



(a) Schematic diagram of apparatus.



(b) Picture of apparatus.

Fig. 1. FSR-6 unsaturated triaxial creep apparatus.

It can be observed from Fig. 2 that the creep behaviors of the sliding zone soils are evident under different matric suctions. In addition, it can be found that the higher the matric suction is, the smaller the creep strain is, which exhibits the impact of unsaturated conditions on soil creep behaviors. It is also worth noting that the acceleration creep behavior was not measured because of the relatively low deviator stress level. Actually, even in high deviator stress level, it is difficult to obtain the acceleration creep behavior in

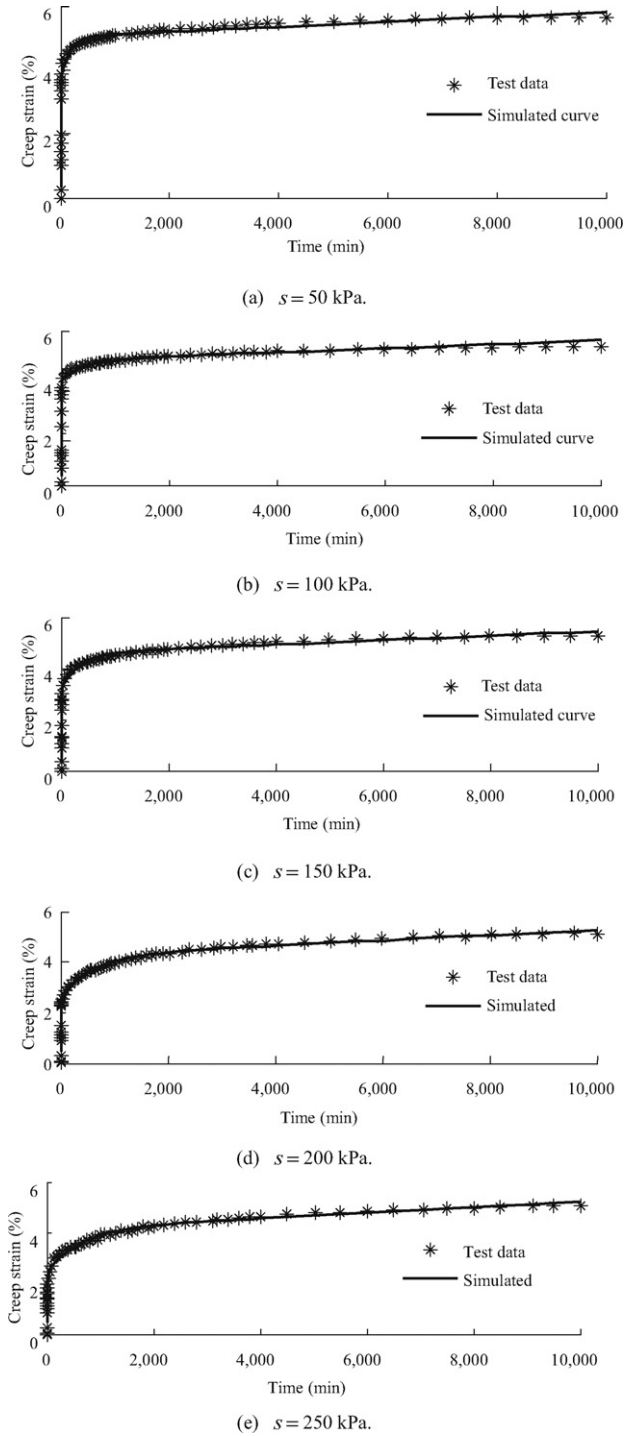


Fig. 2. Results of creep test under different matric suctions.

the laboratory tests. Because the sliding zone soils usually present high plasticity and large plastic strain properties, the acceleration creep behavior will not be considered in this paper.

### 3. Creep model for unsaturated soils

#### 3.1. Burgers creep model

Burgers creep model is mainly composed of Maxwell body and Kelvin body (Fig. 3a). The Maxwell body can be employed to

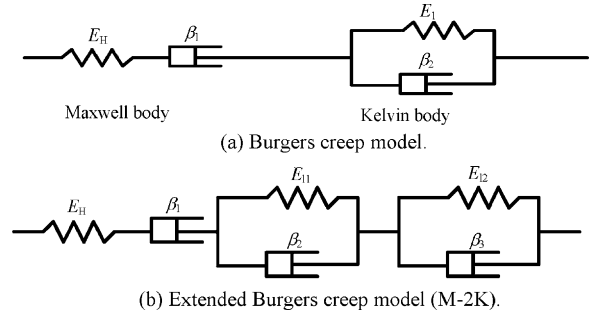


Fig. 3. Sketch of component creep models.

simulate the instantaneous and stationary creep strains of the creep curves under shear stress, and the decreasing creep strain can be simulated by the Kelvin body. Thus, the Burgers model is often used to simulate the visco-elastoplastic creep process of geological materials (Sun, 1999).

Practically, several Kelvin bodies are used in series in the Burgers model, which is known as the extended Burgers model. It exhibits the same creep law as the Burgers model but is more accurate in predicting experimental creep curves. Theoretically, the more Kelvin bodies are put in series into the model, the more precise the creep characteristics of soils can be reflected, whereas the more difficult to determine model parameters for use (Sun, 1999). Therefore, the extended Burgers model with two Kelvin bodies in series, i.e. M-2K creep model, is adopted to fit the experimental creep curves (Fig. 3b). It should be noted that the extended Burgers model does not account for the stage of acceleration creep, which is more complicated and will not be discussed in this paper.

The extended Burgers creep model is developed by inserting another Kelvin body into the Burgers model. The constitutive equation (Sun, 1999) can be written as

$$p_1\sigma + p_2\dot{\sigma} + p_3\ddot{\sigma} + p_4\ddot{\sigma} = q_1\dot{\varepsilon} + q_2\ddot{\varepsilon} + q_3\ddot{\varepsilon} \quad (1a)$$

where

$$p_1 = E_{H1}E_{12} \quad (1b)$$

$$p_2 = \beta_1E_{11} + \beta_3E_{11} + \beta_1E_{12} + \beta_2E_{12} + \frac{E_{11}E_{12}}{E_H} \quad (1c)$$

$$p_3 = \beta_1\beta_2 + \beta_1\beta_3 + \beta_2\beta_3 + \frac{\beta_1\beta_3E_{11}}{E_H} + \frac{\beta_1\beta_2E_{12}}{E_H} \quad (1d)$$

$$p_4 = \frac{\beta_1\beta_2\beta_3}{E_H} \quad (1e)$$

$$q_1 = E_{H1}E_{12}\beta_1 \quad (1f)$$

$$q_2 = E_{H1}\beta_1\beta_3 + E_{12}\beta_1\beta_2 \quad (1g)$$

$$q_3 = \beta_1\beta_2\beta_3 \quad (1h)$$

where  $E_H$ ,  $E_{11}$  and  $E_{12}$  are the elastic moduli of the Maxwell body, the first and second Kelvin bodies, respectively;  $\beta_1$ ,  $\beta_2$  and  $\beta_3$  are the viscosity of Maxwell body, the first and second Kelvin bodies, respectively (see Fig. 3);  $\sigma$ ,  $\dot{\sigma}$ ,  $\ddot{\sigma}$  and  $\ddot{\sigma}$  are the stresses exerted on the Hook body and Newton body of Maxwell body, the first and second Kelvin bodies, respectively.

The creep equation of this model can thus be obtained as

$$\varepsilon(t) = \sigma \left\{ \frac{1}{E_H} + \frac{t}{\beta_1} + \frac{1}{E_{11}} \left[ 1 - \exp\left(-\frac{E_{11}t}{\beta_2}\right) \right] + \frac{1}{E_{12}} \left[ 1 - \exp\left(-\frac{E_{12}t}{\beta_3}\right) \right] \right\} \quad (2)$$

where  $t$  is the time.

### 3.2. Extended Burgers creep model for unsaturated soils

To extend Burgers creep model for unsaturated soils, the stress state in unsaturated soils needs to be analyzed.

According to the theory of elasticity mechanics, the stress state of one point can be expressed by stress tensor ( $s_{ij}$ ) as follows (Xie et al., 2008):

$$s_{ij} = s'_{ij} + s''_{ij} \quad (3a)$$

where

$$s'_{ij} = \sigma_m \delta_{ij} = \frac{1}{3} \sigma_{kk} \delta_{ij} \quad (k = 1, 2, 3) \quad (3b)$$

$$s''_{ij} = s_{ij} - \sigma_m \delta_{ij} \quad (3c)$$

where  $s'_{ij}$  is the spherical stress tensor,  $s''_{ij}$  is the deviator stress tensor,  $\sigma_m$  is the mean stress,  $\delta_{ij}$  is the Kronecker delta, and  $\sigma_{kk}$  is the principal stress.

In the triaxial stress state, by using three invariable stresses  $\sigma_1$ ,  $\sigma_2$ ,  $\sigma_3$ , the stress state can be written as follows:

$$s_{ij} = s'_{ij} + s''_{ij} = \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{bmatrix} \quad (4a)$$

where

$$s'_{ij} = \sigma_m \delta_{ij} = \frac{1}{3} (\sigma_1 + \sigma_2 + \sigma_3) \quad (4b)$$

$$s''_{ij} = s_{ij} - \sigma_m \delta_{ij} = \begin{bmatrix} \sigma_1 - \sigma_m & 0 & 0 \\ 0 & \sigma_2 - \sigma_m & 0 \\ 0 & 0 & \sigma_3 - \sigma_m \end{bmatrix} \quad (4c)$$

Practically, in conventional triaxial creep tests, the axial stress is  $\sigma_1$  and the confining stress is  $\sigma_2 = \sigma_3$ . Fredlund et al. (1978) proposed that the pore air pressure should be added to describe the stress state of one point, which is known as double stress state variables: matric suction and net stress. The matric suction is expressed as

$$s = u_a - u_w \quad (5)$$

where  $u_w$  is the pore water pressure. It can be valued as zero in the drained shear test.

Consequently, the net stress tensor is changed to

$$s_{ij} = s'_{ij} + s''_{ij} = \begin{bmatrix} \sigma_1 - u_a & 0 & 0 \\ 0 & \sigma_2 - u_a & 0 \\ 0 & 0 & \sigma_3 - u_a \end{bmatrix} \quad (6a)$$

where

$$s'_{ij} = \sigma_m \delta_{ij} - u_a \quad (6b)$$

According to the matric suction tensor described in Eq. (5), Eq. (2) can be written in three-dimensional state based on the assumptions (Yan et al., 2010) as follows: (1) the volumetric deformation of materials is flexible, linear, invariable and completed in an instant; (2) the creep deformation is caused by deviator stress tensor, in other words, the spherical stress tensor has no contribution to creep deformation; and (3) the Poisson's ratio does not vary with time.

Therefore, Eq. (2) can be rewritten as

$$\varepsilon_{ij} = \frac{s'_{ij}}{3K} + \frac{s''_{ij}}{3G_H} + \frac{s''_{ij}}{3\eta_1} t + \frac{s''_{ij}}{3G_{11}} \left[ 1 - \exp\left(\frac{-G_{11}t}{\eta_2}\right) \right] + \frac{s''_{ij}}{3G_{12}} \left[ 1 - \exp\left(\frac{-G_{12}t}{\eta_3}\right) \right] \quad (7)$$

where  $G_H$ ,  $G_{11}$  and  $G_{12}$  are the shear moduli of the Maxwell body, the first and second Kelvin bodies, respectively;  $\eta_1$ ,  $\eta_2$  and  $\eta_3$  are the viscous coefficients of the Maxwell body, the first and second Kelvin bodies, respectively; and  $K$  is the bulk modulus, which can be determined by

$$K = \frac{2G_H(1 + \mu)}{3(1 - 2\mu)} \quad (8)$$

where  $\mu$  is the Poisson's ratio.

### 3.3. Parametric study

Parameters of the extended Burgers creep model can be obtained by using nonlinear least squares method, which can be implemented by MATLAB, and details of using this method can be found in Zou and Wang (2010). As the value of  $\mu$  has minor effect on other parameters, it is assumed as 0.4 herein based on experience (Sun, 1999).

Parameters of the extended Burgers creep model under each group of matric suction, as well as the correlation coefficient  $R^2$  of the fitting curves, are summarized in Table 3.

As shown in Table 3, the predicted results using the extended Burgers creep model are in good agreement with the experimental results shown in Fig. 2, with correlation coefficients above 0.98. It indicates that the reasonable predication of the creep behaviors of the unsaturated soils can be given by the extended Burgers creep model.

In order to further investigate the relationship between parameters of the extended Burgers creep model and matric suction, the plots of model parameters versus matric suction (normalized by dividing the standard atmospheric pressure  $P_a$ , which equals 101.325 kPa) are presented in Fig. 4.

As it can be seen from Fig. 4, the obvious linear relationship exists between the model parameters ( $G_H$ ,  $G_{11}$ ,  $G_{12}$ ,  $\eta_1$ ) and matric suction ( $s$ ); and it can be expressed by the linear function  $y = ax + b$ , where  $a$  and  $b$  are the correlation coefficients. When the matric suction is increased,  $G_H$  and  $\eta_1$  show a linear increasing trend, but  $G_{11}$  and  $G_{12}$  display a linear decreasing trend, i.e. the elasto-plastic deformation of the samples decreases with the increasing matric suction.

In Eqs. (6a) and (6b), we can see that the maximum value of visco-elastic deformation depends on the values of  $G_{11}/\eta_2$  and  $G_{12}/\eta_3$ , thus the values of  $G_{11}/\eta_2$  and  $G_{12}/\eta_3$  were considered as variables, and the relationships with the matric suction are illustrated in Fig. 5.

In Fig. 5, a linear relation also exists between the values of  $G_{11}/\eta_2$ ,  $G_{12}/\eta_3$  and matric suction  $s$ , which can also be written by the linear function  $y = ax + b$ . When the matric suction is increased, the values of  $G_{11}/\eta_2$  and  $G_{12}/\eta_3$  show a linear decreasing trend, indicating that the maximum value of visco-elastic deformation decreases with the increasing matric suction.

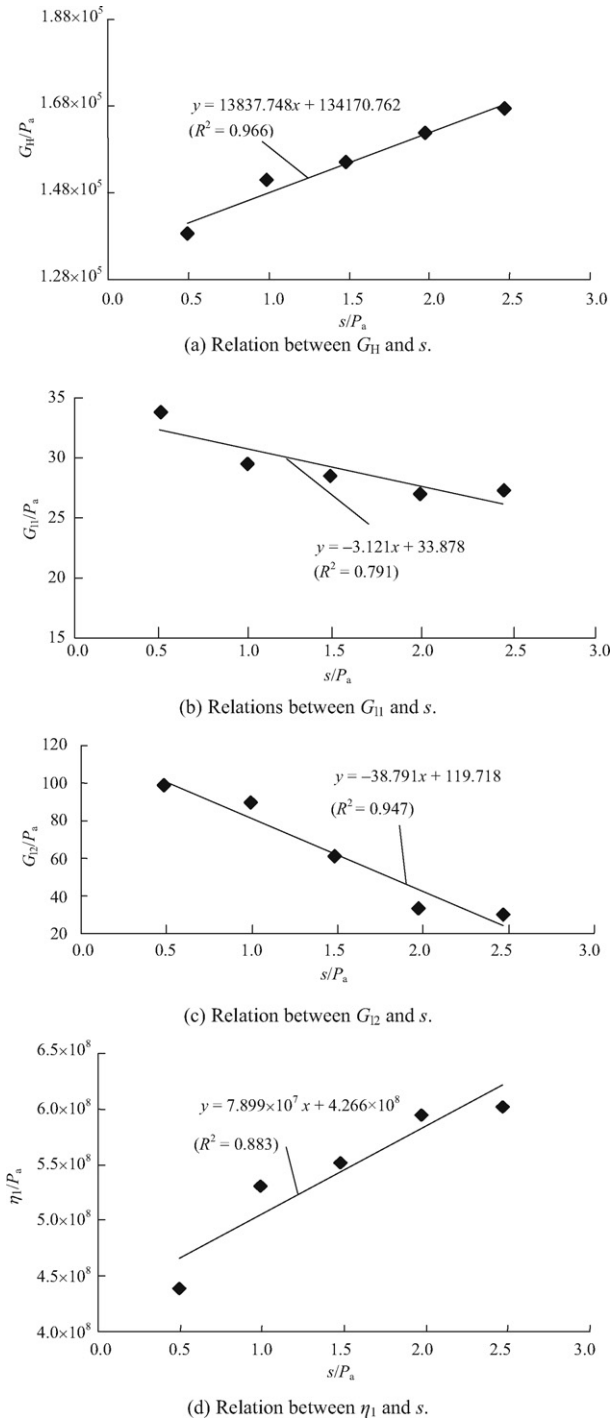
### 3.4. Modified Burgers creep model

Given the parameters of the Burgers creep model vary with matric suction, the Burgers creep model is modified as follows:

$$\varepsilon_{ij} = \frac{s'_{ij}}{3K'} + \frac{s''_{ij}}{3G_H} + \frac{s''_{ij}}{3\eta_1} t + \frac{s''_{ij}}{3G'_{11}} \left[ 1 - \exp\left(\frac{-G'_{11}t}{\eta'_2}\right) \right] + \frac{s''_{ij}}{3G'_{12}} \left[ 1 - \exp\left(\frac{-G'_{12}t}{\eta'_3}\right) \right] \quad (9a)$$

**Table 3**  
Parameters of the extended Burgers creep model.

Group	$G_H$ (MPa)	$G_{11}$ (GPa)	$G_{12}$ (kPa)	$\eta_1$ (MPa min)	$\eta_2$ (kPa min)	$\eta_3$ (kPa min)	$R^2$
1	139	439	33.8	65.2	98.2	169	0.99
2	151	531	29.6	75.9	88.8	260	0.99
3	155	551	28.5	106	61.1	271	0.99
4	162	595	27	155	33	122	0.98
5	167	602	27.4	171	30.4	225	0.98



**Fig. 4.** Normalized relations between parameters of the extended Burgers model and matric suction.

where

$$K' = \frac{2(1 + \mu)}{3(1 - 2\mu)} G_H \quad (9b)$$

$$G'_H = a_{G_H} \frac{s}{P_a} + G_H^0 \quad (9c)$$

$$G'_{11} = a_{G_{11}} \frac{s}{P_a} + G_{11}^0 \quad (9d)$$

$$G'_{12} = a_{G_{12}} \frac{s}{P_a} + G_{12}^0 \quad (9e)$$

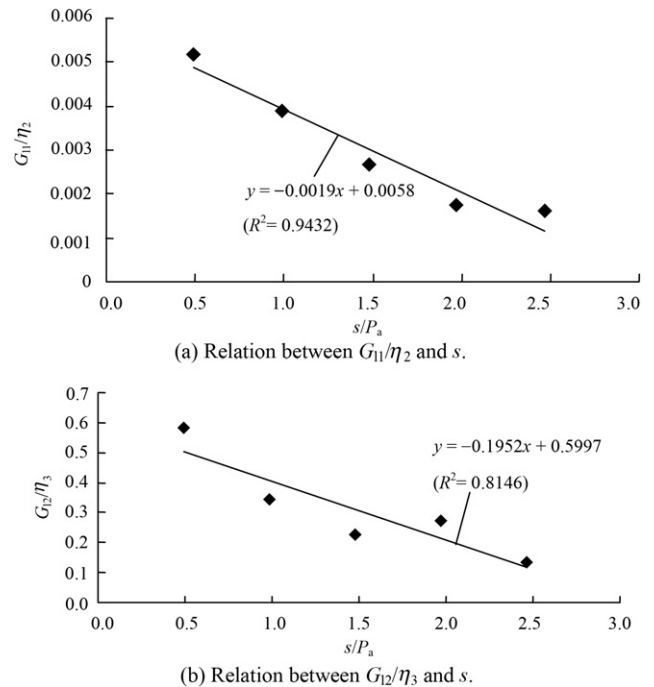
$$\eta'_1 = a_{\eta_1} \frac{s}{P_a} + \eta_1^0 \quad (9f)$$

$$\frac{G'_{11}}{\eta'_2} = a_{G_{11}/\eta_2} \frac{s}{P_a} + \left(\frac{G_{11}}{\eta_2}\right)^0 \quad (9g)$$

$$\frac{G'_{12}}{\eta'_3} = a_{G_{12}/\eta_3} \frac{s}{P_a} + \left(\frac{G_{12}}{\eta_3}\right)^0 \quad (9h)$$

In saturated soils, the matric suction  $s$  is considered to be 0, thus  $G_H^0, G_{11}^0, G_{12}^0, \eta_1^0, (G_{11}/\eta_2)^0, (G_{12}/\eta_3)^0$  can be considered as the parameters under saturated condition; and  $a_{G_H}, a_{G_{11}}, a_{G_{12}}, a_{\eta_1}, a_{G_{11}/\eta_2}, a_{G_{12}/\eta_3}$  can be considered as the influence coefficients of parameters corresponding to the matric suction.

In order to calibrate the modified Burgers creep model, another group of test data is employed. This group of test soils is the same as other several groups, which can be considered that their creep parameters are alike. Keeping the net confining pressure and deviator stress level of this group of experiment as same as other several



**Fig. 5.** Normalized relations of  $G_{11}/\eta_2$  and  $G_{12}/\eta_3$  with matric suction  $s$ .



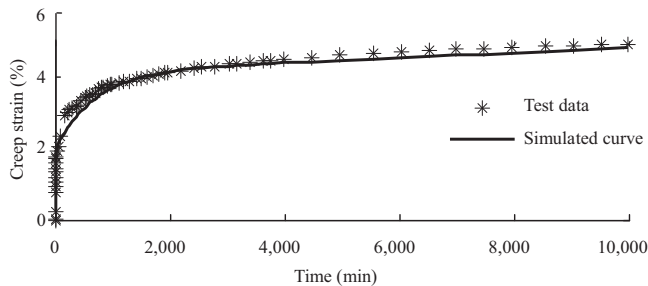


Fig. 6. Results of creep test under matrix suction of 300 kPa.

groups, and the matrix suction of 300 kPa, the simulated results are shown in Fig. 6.

It can be seen from Fig. 6 that the simulated curve also fits test data well with the correlation coefficient of 0.93, which proves that this modified Burgers creep model is reasonable and effective.

#### 4. Conclusions

The unsaturated soils in the sliding zone exhibit evident creep behaviors. Based on detailed analysis, some conclusions can be drawn as follows:

- (1) The extended Burgers creep model for unsaturated soils in triaxial stress state was derived, and all of parameters under various matrix suctions were obtained. The simulated results are in good agreement with the experimental results, with correlation coefficients above 0.98.
- (2) Relations between parameters of the extended Burgers creep model and matrix suctions were discussed, and a linear relation was found between them. The elasto-plastic deformation and the maximum value of visco-elastic deformation of the soil samples decrease with the increasing matrix suction.
- (3) Considering the relations between parameters of the extended Burgers creep model and matrix suction, a modified Burgers creep model was developed and calibrated by another group of creep test. The test results show that the modified Burgers creep model is reasonable and effective.

Creep behaviors of sliding zone soils are rather complex, especially in unsaturated situation. In this paper, just one level of net confining pressure and deviator stress was discussed. However, in

order to better understand and model the creep behavior of unsaturated sliding zone soils, more levels of net confining pressures and deviator stresses should be considered in further studies.

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