

Article

Mechanical Behavior of Weathered Granite Exposed to Water

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Abstract: Weathered granite has been widely used as an emerging foundation filler for constructing transportation infrastructure. However, various softened rocks weathered due to exposure to water have special properties. Thus, it is necessary to gain a thorough understanding of the various physical and mechanical properties of weathered granite after exposure to water in order to avoid engineering accidents. To this end, this paper conducted a series of undrained triaxial shear tests to compare the mechanical behavior of weathered granite in natural and saturated states. The results demonstrate that the strength of the weathered granite significantly declines when it is exposed to water, and it exhibits noticeable water softening characteristics. Consolidation methods also affect the mechanical properties of weathered granite. The degree of softening of weathered granite decreases with an increase in the deviator stress imposed by the deviator stress consolidation. Subsequently, we established an empirical model for the strain softening of weathered granite suitable for natural and saturated conditions. This model took the elastic modulus of weathered granite before the peak strength as a measure and introduced the strength parameters of the internal friction angle (φ) and the internal cohesion (c). First, the fitted function correlating c and φ with the plastic internal variable was determined, and then the relationship between the strength and the strain-softening parameters was established so as to obtain the complete stress–strain curve of the granite rock. Finally, validation studies were performed to address the capability of the model to predict permanent deformation. It provides a theoretical basis for predicting and calculating the strain softening of weathered granite exposed to water.

Keywords: weathered granite; mechanical behavior; strain softening; deviator stress consolidation; empirical model



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1. Introduction

Under the action of natural (i.e., physical, chemical, and biological) weathering, the original structure of rocks is destroyed and loosened, their chemical composition changes, new chemical minerals are formed, and their mechanical properties weaken. Due to the many factors controlling the weathering of rocks (i.e., rock characteristics and climatic and topographical conditions), weathered rocks possess different mineral compositions and structures. In most cases, the degree of weathering of a weathered rock diminishes from the surface to the bottom of the rock, and it is distributed in a zonal pattern. Weathered rock obviously differs from other rocks, but it is similar to soft rock. Water–rock interactions cause the microstructure of the rock to change and metasomatize [1]. The interactions between water and rock (body) cause the rock (body) to soften and disintegrate, resulting in the remarkable degradation of its engineering properties.

Due to the convenience and low price of materials, weathered granite has been widely used as an emerging foundation filler for constructing transportation infrastructure [2,3].

Zhang [4] found that weathered granite has strong shear cohesion after compaction by direct shear tests. Zhou et al. [5] conducted dynamic triaxial tests on five fully weathered granites, analyzed the effects of load ratio, critical dynamic stress, and loading times on fully weathered granite, and found that long-term cyclic loading has limited impact on the settlement of fully weathered rock subgrades. In addition, weathered rock has also been used as a foundation for the establishment of some reservoirs [6,7]. Studying water–rock interactions is one of the topics at the frontier of geotechnical engineering. The physical, chemical and mechanical processes of rock under certain osmotic pressure or hydrodynamic conditions are the fundamental cause of deformation and failure of engineering rock mass [8–10].

Weathered granite widely distributed in the South China Sea (see Figure 1) belongs to types of special sedimentary rocks that are relatively complete and hard and have good mechanical properties in their natural state [11,12]; nonetheless, they quickly swell, disintegrate, and soften after exposure to water, resulting in a significant decrease in their mechanical properties. Therefore, research on these rocks is of great significance.

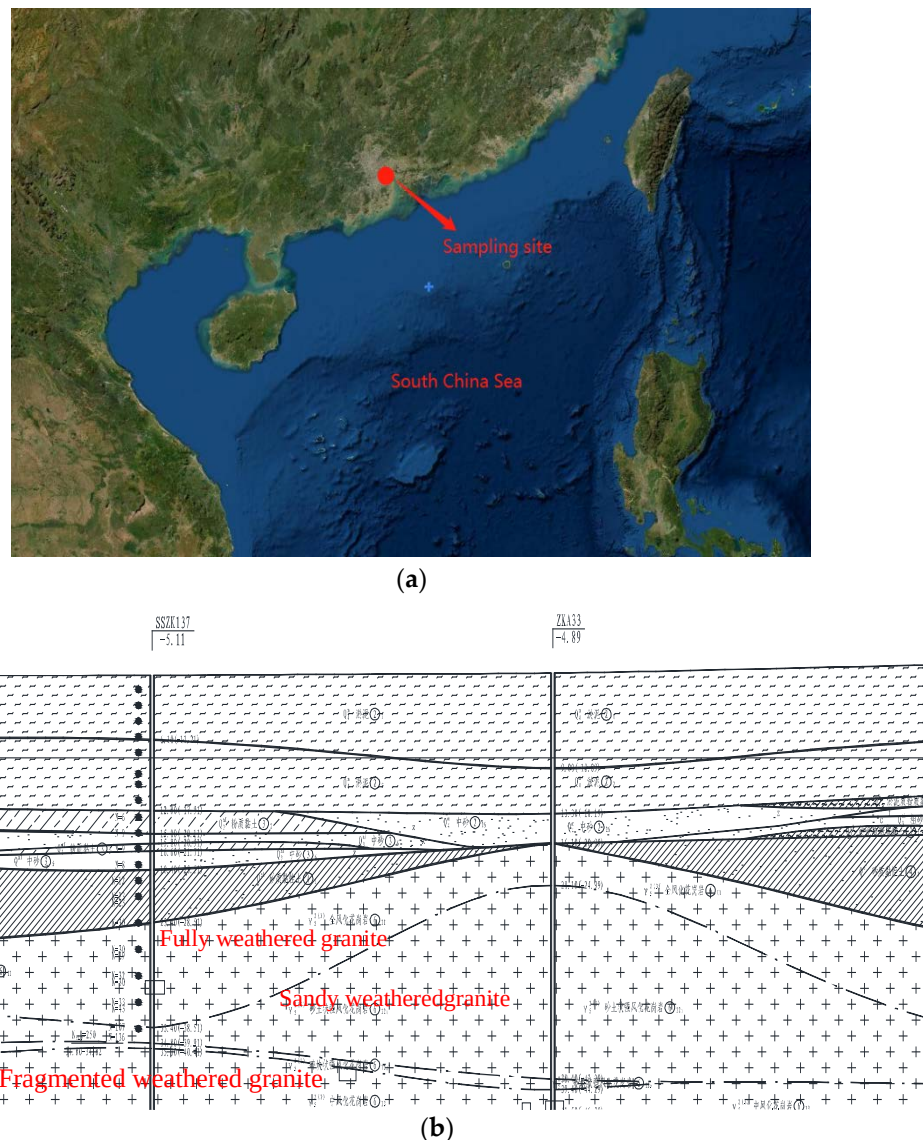


Figure 1. The distribution area of the studied weathered rock: (a) Sampling site; (b) Geological section of the sampling site (From the engineering geology report of the Shenzhen-Zhongshan Bridge).

Early scholars have conducted ample research on the softening characteristics of mudstone, shale, and other soft rocks exposed to water and have achieved rich data on the mechanism for the softening of rocks in contact with water [13–15]. For instance, on the basis of experimental research, Eliek [16] found that the Pittsburgh red mudstone contains minerals that swell in contact with water. Thus, these mudstones decompose after exposure to water, and their strength continues to decrease under seasonal dry–wet and freeze–thaw cycles. Hawkins [17] conducted a triaxial shear test on a disintegrable rock rich in hydrophilic clay minerals and found that the disintegration and siltation of the rock caused by the expansion due to water absorption and the uneven shrinkage fragmentation due to water loss are the main reason for the rock softening in the presence of water. In another work, Zheng et al. [18] discussed the softening mechanism of a shale in northwest Hubei through microscopic and macroscopic experiments and believed that the saturation time affected the compressive strength and elastic modulus of the rock. However, there are few works on special soft rocks such as weathered rock, and the research on the mechanical properties of weathered rocks softened by water is even scarcer.

Many efforts have been devoted to explaining the strain-softening phenomenon that occurs after a rock reaches its peak strength, so a corresponding strain-softening model is established to describe the softening characteristics of the rock. Gurson [19] also developed a meso-level constitutive model to examine the influence of microvoid damage on the deformation behavior of materials. Krajcinovic et al. [20,21] established a damage statistical constitutive model of rock strain softening from the perspective of the randomness of the distribution of defects in the rock material and the view that the strength of the rock microelement obeys the Weibull distribution. Darabi et al. [22] also studied the phenomenon of damage recovery and then proposed a meso-damage constitutive model. However, all the above models describe the strain softening of natural rocks; thus, since the mechanical properties of weathered rocks are significantly different from those of natural rocks, these models cannot explain the strain-softening behavior of weathered rocks. Therefore, it is necessary to study the mechanical properties of weathered rocks and develop a strain-softening model for describing the softening characteristics of weathered rocks.

This study conducted a series of drained triaxial shear tests on a weathered rock for the above reasons. The trend of the change in the mechanical properties of the weathered rock before and after exposure to water was analyzed and compared, and the reason for the variation in the strength of the weathered rock after exposure to water was clarified. In addition, the elastic modulus of the rock mass before the peak strength was considered to be a constant quantity, and the relationship between the strength parameter and the strain-softening parameter was established. This research aims to better understand the mechanical properties of weathered rock by examining its strain softening before and after exposure to water. It can provide a specific theoretical basis for designing and constructing current and future submarine transportation facilities.

2. Materials and Methods

2.1. Testing Materials

This study selected the undisturbed weathered granite in the base layer of the South China Sea bed for analysis. This type of weathered rock is composed of various mineral components, is yellowish brown, and is widely distributed in the South China Sea, as shown in Figures 1 and 2. It is characterized as the fourth phase of Yanshan intrusive rock, and Table 1 summarizes its properties.



Figure 2. The images of the weathered rock sample.

Table 1. The basic physical and mechanical parameters of the testing rock samples.

Property	Fully Weathered Granite	Sandy Weathered Granite	Fragmented Weathered Granite
Natural water content (w)	25.78%	17.30%	18.80%
Specific gravity (G_s)	2.7	2.68	2.65
Void ratio (e)	0.79	0.62	0.54
Liquid limit (W_L)	31.59%	29.56%	26.78%
Plastic limit (W_P)	14.52%	12.77%	11.45%

The samples discussed in this research are taken from a depth of 30–40 m lower than the groundwater level. Therefore, the testing rock sample is initially saturated. After a drill extracts the sample, it is placed in a thin-walled sampler with a diameter of 76.2 mm. In order to maintain the original characteristics of the extracted sample to the greatest extent, the sample is sealed with wax and medical tape and stored in a room at a constant temperature before the indoor test.

2.2. Testing Equipment and Specimen Preparation

This study uses an electromechanical dynamic triaxial apparatus (GDS Instruments Ltd., the UK) as the test equipment (see Figure 3) [23]. The equipment can perform static and dynamic triaxial tests and has a high precision of measurement, control, and data processing accuracy. The equipment is used for indoor dynamic triaxial tests at a maximum loading confining pressure of 2 MPa, a loading frequency in the range of 0.1–5.0 Hz, and a maximum, applicable dynamic load of 10 kN. Before the test starts, all the sensors and controllers connected to the pressure chamber and the test system need to be calibrated. The sample used in this research is a standard cylindrical sample with a diameter and height of 50 and 100 mm respectively, widely used in previous studies [24,25].

After removing the residual weathered rock at both ends of the sampler, we cut the rock into standard test specimens with a diameter of 50 mm and a height of 100 mm. Each sampler can produce three standard specimens. After the specimens are prepared, they are placed into a saturator immediately, and filter paper and permeable stone are pasted on both ends of the saturator.

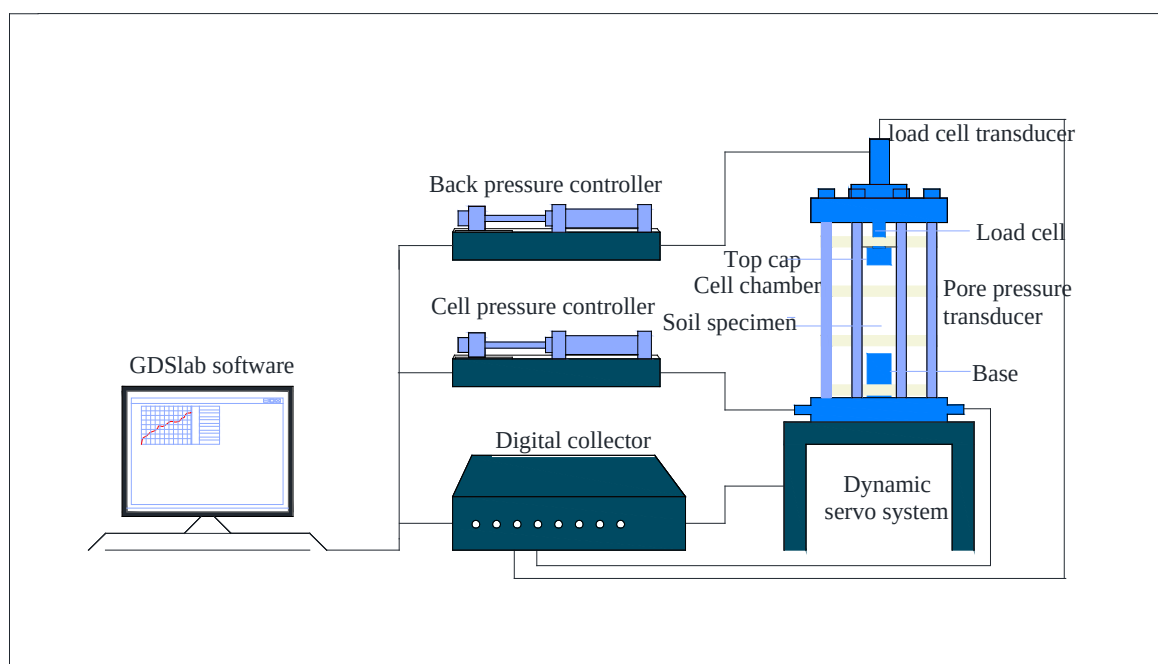


Figure 3. The instrument for performing the dynamic triaxial tests.

2.3. Experimental Procedures

Considering that the rock mass chiefly undergoes a shear failure, this test adopted a conventional triaxial undrained shear test to investigate the mechanical properties of the weathered rock after being softened by water. After the specimens were prepared, they were divided into two groups: One group was placed in a saturator for 4 h at a pressure of -0.1 MPa for vacuum saturation and then directly subjected to the triaxial test (the natural state), and the other group was subjected to an indoor soaking treatment. The saturator with the rock samples was soaked in a pre-prepared bucket for about 15 days, the same as the actual soaking time of the rock sample at the sampling site (the saturated state). The sample was then mounted on a triaxial instrument for the second saturation, and the air bubbles were dissolved by applying a back pressure of 50 kPa. When B (Saturation index) value > 0.95 , the saturation operation was complete [26].

The isotropic consolidation at a confining pressure of 600 kPa and back pressure of 100 kPa and the deviator stress consolidation according to the set adequate confining pressure was performed. The deviator stress consolidation uses two effective confining pressures ($\sigma_1 - \sigma_3 - 1 = 150$ kPa, $\sigma_1 - \sigma_3 - 2 = 300$ kPa; σ_1 is the first principal stress, and σ_3 is the third principal stress) for the consolidation: a confining pressure of 200 kPa and back pressure of 50 kPa; a confining pressure of 500 kPa and back pressure of 200 kPa. When the isotropic consolidation is used, the pore pressure gradually declines to close to the back pressure and stabilizes. At this time, the sample consolidation is complete. When the deviator stress is used for consolidation, the pore pressure gradually decreases and then stabilizes. Indeed, the corresponding deviator stress is continuously applied, and the pore pressure gradually declines to close to the back pressure and stabilizes. To ensure that the consolidation does not produce pore pressure, we set the consolidation time at 48 h. Three effective pressures (p) of 500, 600, and 680 kPa were examined, and all the shear tests were axial-strain-controlled at a rate of $0.01\% \cdot \text{min}^{-1}$ during shearing and terminated at a strain of 30%. The detailed program of the 18 triaxial shear tests is presented in Table 2.

Table 2. The test plan of the triaxial shear tests conducted in the current study.

Test ID	State Before Test	Specimen Type	Consolidation Method	p (kPa)	
SA-1	Natural	Fully weathered granite	Isotropic consolidation	500	
SA-2			$(\sigma_1 - \sigma_3)_1$		
SA-3			$(\sigma_1 - \sigma_3)_2$		
SB-1	Saturated		Isotropic consolidation		600
SB-2			$(\sigma_1 - \sigma_3)_1$		
SB-3			$(\sigma_1 - \sigma_3)_2$		
SC-1	Natural	Isotropic consolidation	680		
SC-2		$(\sigma_1 - \sigma_3)_1$			
SC-3		$(\sigma_1 - \sigma_3)_2$			
SD-1	Saturated	Isotropic consolidation		680	
SD-2		$(\sigma_1 - \sigma_3)_1$			
SD-3		$(\sigma_1 - \sigma_3)_2$			
SE-1	Natural	Isotropic consolidation	680		
SE-2		$(\sigma_1 - \sigma_3)_1$			
SE-3		$(\sigma_1 - \sigma_3)_2$			
SF-1	Saturated	Isotropic consolidation		680	
SF-2		$(\sigma_1 - \sigma_3)_1$			
SF-3		$(\sigma_1 - \sigma_3)_2$			

Note: $(\sigma_1 - \sigma_3)_1$ and $(\sigma_1 - \sigma_3)_2$ respectively indicate that deviator stress of 30% and 60% of the effective confining pressure is applied for the consolidation.

3. Test Results

3.1. Stress and Axial Strain

Figure 4 delineates the stress–strain relationship of the fully weathered granite in the triaxial undrained shear test. According to Figure 4a–c, the stress–strain curve of the fully decomposed granite shows that the shear stress (q) gradually enlarges with an increase in the axial strain before the shear stress on the sample reaches the peak. After reaching the peak, the shear stress gradually decreases with an increase in the axial strain. This observation agrees with the studies of Zhao (2004) [27] and Niu (2016) [28] on fully weathered granite. From the peak stress marked in the figure, it can be inferred that the strength of the fully weathered granite in the saturated state is significantly lower than that in the natural state, and the peak strength can decline by up to about 20%, indicating that the mechanical properties of the fully decomposed granite continuously deteriorate under the interactions between water and rock, and its shear strength remarkably declines.

The stress–strain curve of the fully weathered rock in its natural state can be roughly divided into three stages, as shown in Figure 4d. In the initial stages of the loading (an axial displacement in the range of 0–10%), as the axial strain increases, the shear stress on the specimen soars, that is, a slight change in the shear stress produces a substantial axial displacement (Zhao, 2005 [29]; Liu, 2016 [30]). At this time, there is an approximately linear relationship between the shear stress and the displacement, and the slope of the stress–strain curve is steep. When the axial displacement exceeds about 10%, the trend of the change in the axial strain with the shear stress varies, the slope of the stress–strain curve decreases, and the stress–strain curve gradually plateaus. Finally, when the axial strain of the sample exceeds about 16% (10% in Zhao’s study [29]), the sample enters the softening stage; that is, the shear stress gradually declines with an increase in the axial strain.

In addition, the various consolidation methods affect the test results differently. The shear strength of the rock sample under the deviatoric consolidation condition is always higher than that under the isotropic consolidation. The shear strength enlarges with an increase in the deviator stress applied by the deviator stress consolidation. The stress–strain curve of the weathered granite in the saturated state is quite different from that in the natural state.

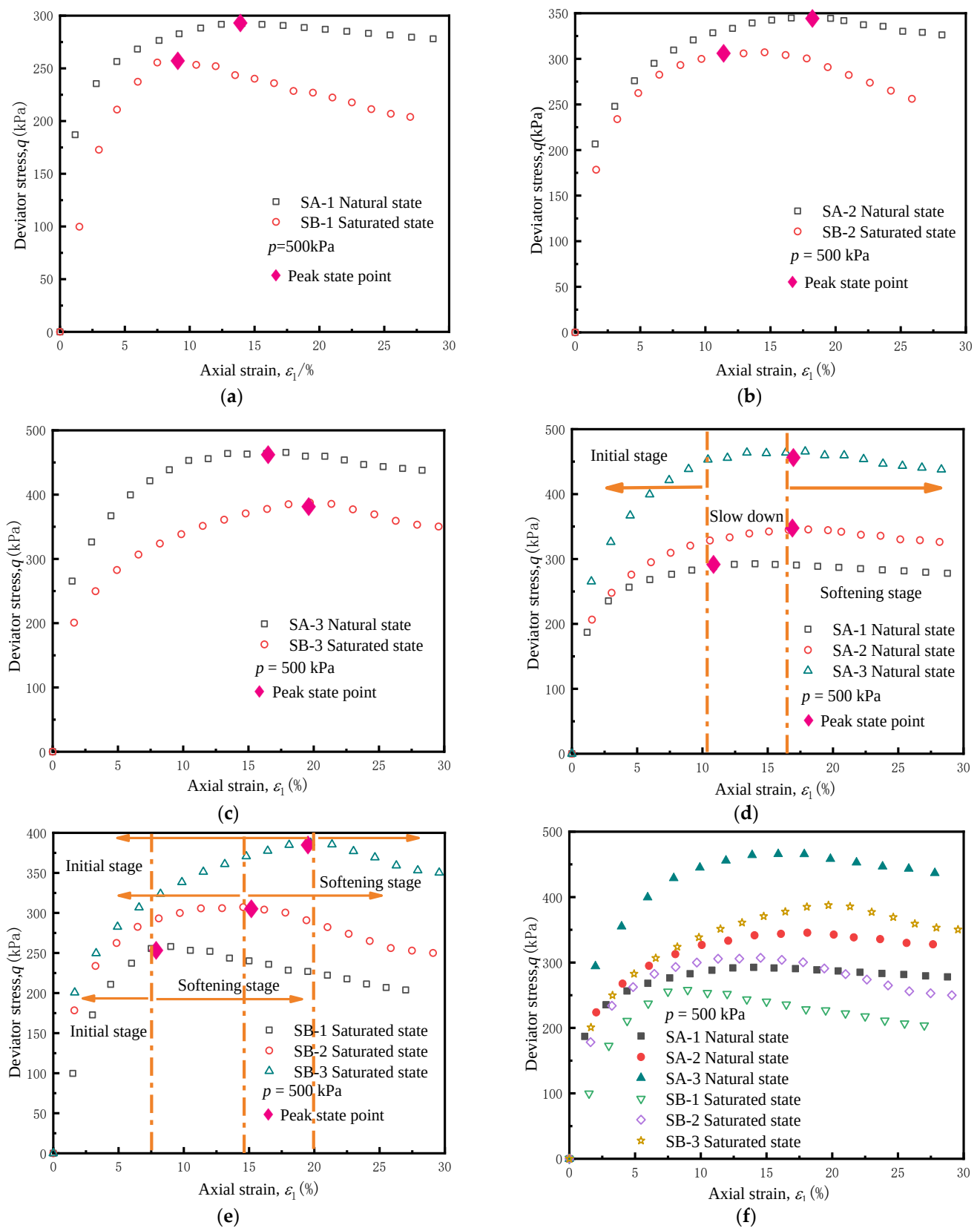


Figure 4. The stress–strain relationship of the fully weathered granites: (a) Isotropic consolidation; (b) Deviator stress (30%); (c) Deviator stress (60%); (d) Natural state; (e) Saturated state; (f) Comparison of stress–strain curves between saturated state and natural state.

Further, except for the individual sample (SB-2), the stress–strain curve of the other samples has only two stages, namely the initial stage and the softening stage, as shown in Figure 4e. When the sample reaches the peak stress, it immediately enters the softening stage (Zhang, 2019 [31]). The initial slope of the stress–strain curve in the saturated state is steeper than that in the natural state, and the strain-softening amplitude of the sample in the saturated state is more noticeable. Similarly, the stress–strain curve of the saturated, fully weathered granite under different consolidation conditions is consistent with its stress–strain curve in the natural state.

In general, the above results demonstrate that the strength of the fully weathered rock deteriorates when it is exposed to water, and its strain-softening characteristics are more prominent in the saturated state because water diffuses through the mineral particles along the tiny cracks and pores inside the rock sample during the immersion process. The lubrication and softening effect of water reduces the internal cohesion (c) and the internal friction angle (φ) of the fully weathered granite to various degrees.

Figure 5 depicts the stress–strain curves of the sandy fully weathered granite under different consolidation conditions in the saturated and natural states. Like the fully weathered granite, the stress–strain curve of the rock in the natural state can be roughly divided into three stages: an axial strain of 0–8%, 8–17.5%, and higher than 17.5%. However, compared with fully weathered granite, the slope of the stress–strain curve of the sandy weathered granite in the softening stage is gentler, as shown in Figure 5d; in other words, the degree of strain softening of the rock declines relatively.

When the axial strain exceeds about 20%, the attenuation amplitude of the deviator stress on the sample is minimal, implying a specific strain-hardening trend. Figure 5e shows that the degree of the strain softening of the sandy weathered granite in the saturated state after reaching the peak shear stress is significant. Especially for the specimen under the isotropic consolidation, the stress attenuation after the stress peak is about 28% of the peak strength. Thus, the interactions between water and rock markedly affect the sandy weathered rock. Moreover, changing the consolidation method from isotropic to 60% deviator stress consolidation raises the axial strain of the rock sample when it reaches the peak stress and increases the shear strength of the weathered rock, which indicates that the deviator stress consolidation has a good effect on the sandy weathered granite.

The above results demonstrate that the state of the rock sample, namely the natural or saturated state, impacts on the softening of the sandy weathered rock because water diffuses into the rock mass through pores or cracks, which gives rise to uneven stress inside the rock mass, thereby causing the soil to disintegrate along the direction of the pores and cracks and destroying the soil structure.

Figure 6 plots the deviator stress (q) versus the axial strain of the fragmented weathered granites under different consolidation conditions in the saturated and natural states. Except for the saturated sample, all the other samples have different degrees of strain hardening after reaching the peak stress, especially because the fragmented weathered rock is composed chiefly of large pores and a few small pores. The large pores make the water and the internal particles of the rock contact each other completely, which causes the rock to be more prone to disintegration, thereby leading to more significant deformation. Isotropic consolidation, the strain hardening of the rock sample, is more evident.

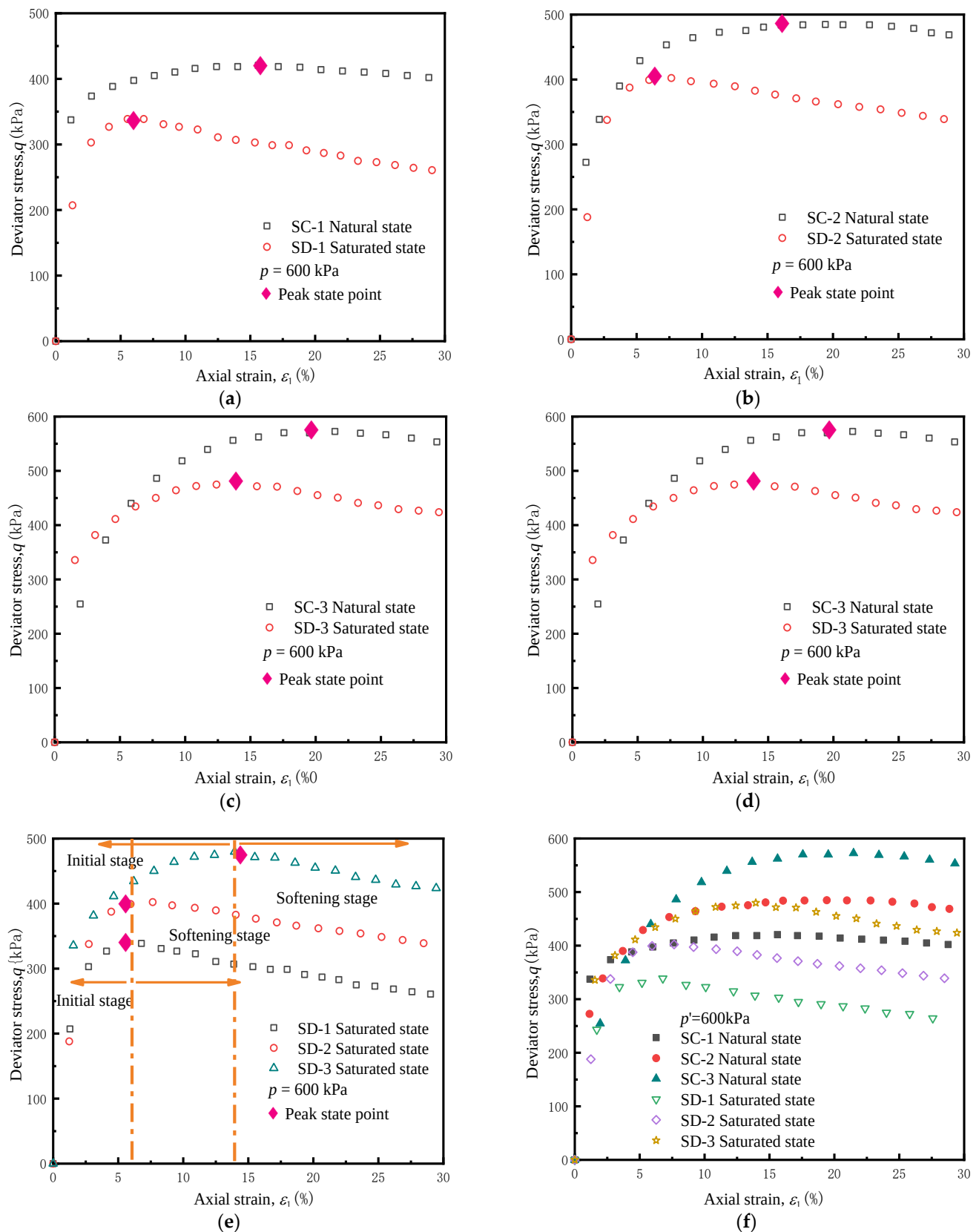


Figure 5. The stress–strain relationship of the sandy weathered granites: (a) Isotropic consolidation; (b) Deviator stress (30%); (c) Deviator stress (60%); (d) Natural state; (e) Saturated state; (f) Comparison of stress–strain curves between saturated state and natural state.

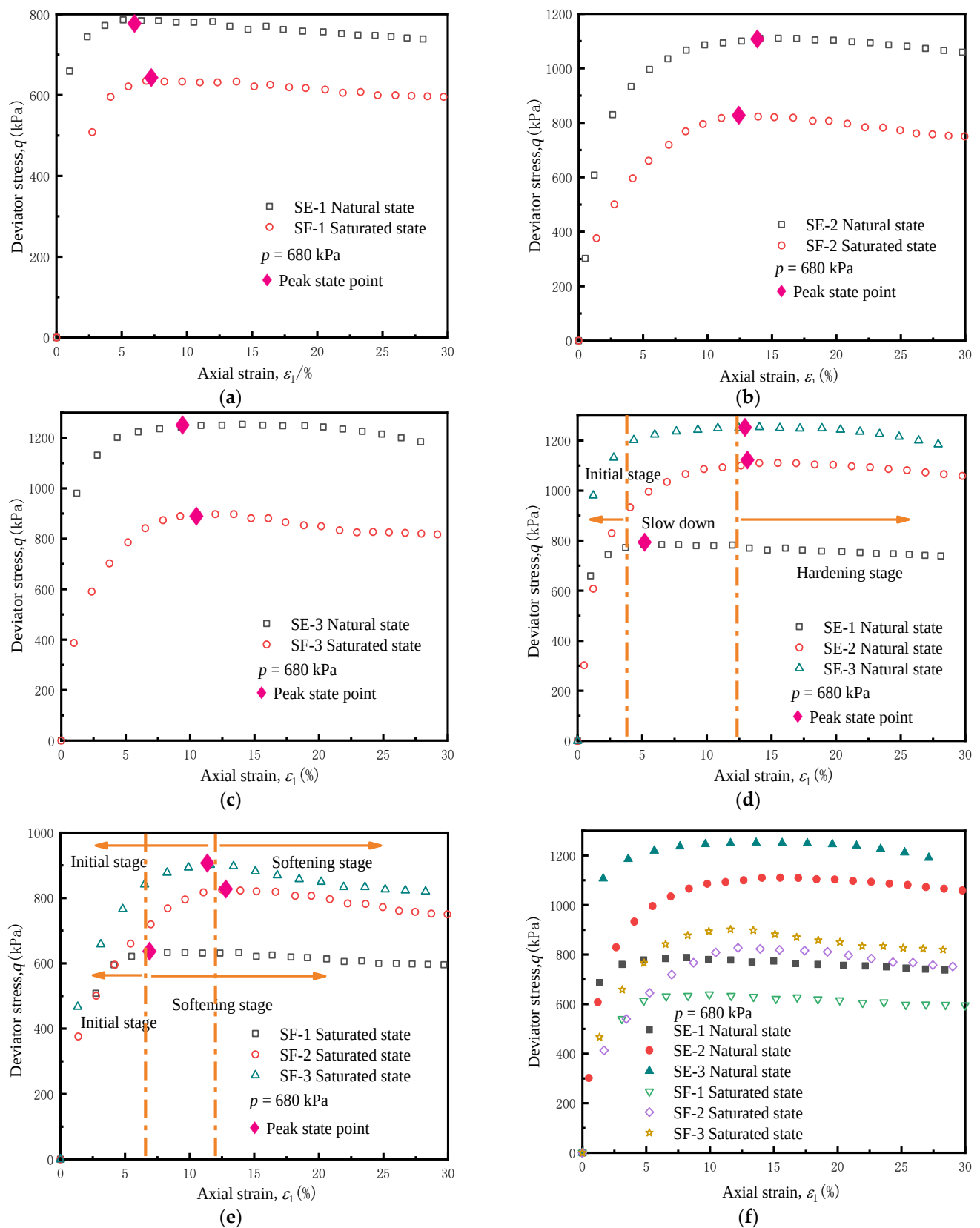


Figure 6. The stress–strain relationship of the fragmented weathered granites: (a) Isotropic consolidation; (b) Deviator stress (30%); (c) Deviator stress (60%); (d) Natural state; (e) Saturated state; (f) Comparison of stress–strain curves between saturated state and natural state.

3.2. Pore Pressure and Axial Strain

Figure 7 portrays the development curve of the pore pressure (μ) with the axial strain. In the initial stages, the pore pressure continues to increase with the axial strain. When the axial strain reaches the peak strain (usually around 5%), the pore pressure curve gradually slows down, and the pore pressure follows a decreasing trend, indicating that the weathered granite exhibits the characteristics of an over-consolidated soil during the shearing process. In the initial stages of the loading, the shear shrinkage (the pore water pressure) increases, and as the axial strain continues to rise, the sample shows a trend of shear dilatancy until it reaches a critical state. Figure 7a–c also demonstrates that the pore water pressure first increases but then decreases. In addition, comparing the pore pressure curves with the deviator stress curves reveals that, except for the particular samples (SB-2 and SF-3), the axial strain required for the shear stress to reach the peak value ($>5\%$) is always greater than the axial strain required for the dilatancy to occur ($\leq 5\%$), implying that the weathered granite sample has a process of transition from shear shrinkage to dilatancy before reaching the peak stress.

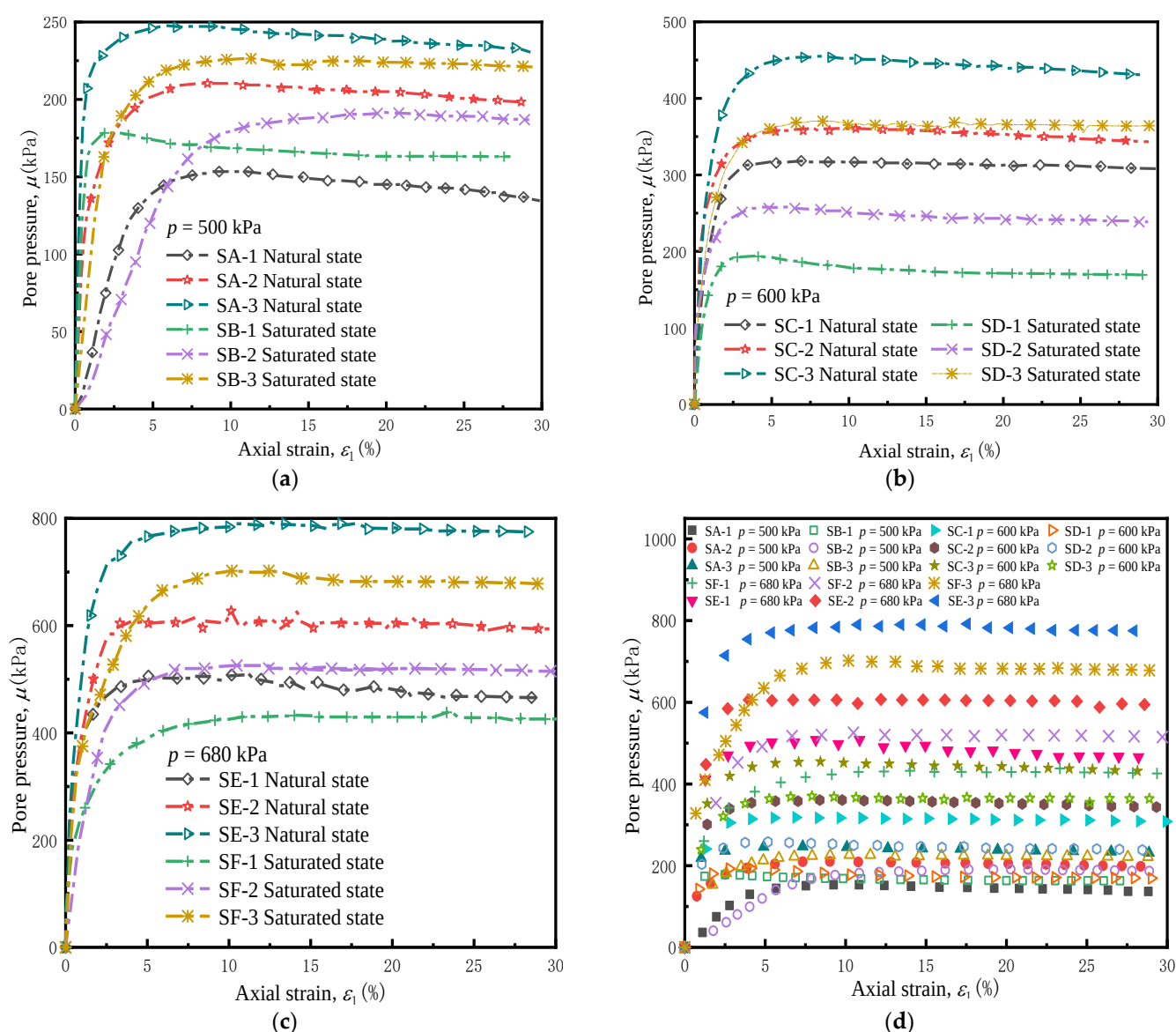


Figure 7. The relationship between the pore pressure and the axial strain of the weathered granites: (a) Fully weathered granites; (b) Sandy weathered granites; (c) Fragmented weathered granites; (d) Pore pressure curve of test specimen.

3.3. Strength Degradation Index

This paper employs the ratio of the peak stress on the weathered granite sample in the saturated state to that in the natural state under the same confining pressure obtained from the experiment as the strength degradation index:

$$\delta_r = \frac{q_{n,\max}}{q_{s,\max}} \quad (1)$$

where δ_r represents the strength degradation index of the weathered granite, $q_{n,\max}$ denotes the peak stress on the weathered granite in its natural state, and $q_{s,\max}$ is the peak stress on the weathered granite in its saturated state.

This paper uses the strength degradation index defined above to describe the degree of water softening of the weathered granite samples under different consolidation conditions. The smaller the strength degradation index is, the higher the degree of the water softening of the weathered granite sample becomes. The results of the degradation index are presented in Table 3. The strength degradation index under the conditions of isotropic consolidation, the deviator stress consolidation with 30% deviatoric stress, and the deviator stress consolidation with 60% deviator stress is, respectively, 0.91, 0.89, and 0.82 for the fully weathered granite; 0.85, 0.83, and 0.81 for the sandy weathered granite; and 0.81, 0.75, and 0.72 for the fragmented weathered granite.

Table 3. The peak strength and degradation index of the weathered granite under the different consolidation conditions and in the various rock states.

Specimen Type	Consolidation Method	$q_{n,\max}$ (kPa)	$q_{s,\max}$ (kPa)	δ_r
Fully weathered granite	0	292.63	267.03	0.91
	0.3	343.77	305.89	0.89
	0.6	460.75	375.81	0.82
Sandy weathered granite	0	400.46	338.74	0.85
	0.3	484.22	402.20	0.83
	0.6	575.96	469.73	0.81
Fragmented weathered granite	0	783.96	633.31	0.81
	0.3	1109.74	827.09	0.75
	0.6	1249.13	901.40	0.72

Note: In the Consolidation method column, 0, 0.3, and 0.6 indicate the isotropic consolidation, the deviator stress consolidation with 30% deviator stress, and the deviator stress consolidation with 60% deviator stress, respectively.

4. Modeling

4.1. Model for Predicting Strain Softening

Under the action of excavation and unloading, the settlement of the foundation caused by the strain and softening of weathered rock is an essential part of the post-construction of an immersed tube tunnel. Therefore, the establishment of a strain-softening model to describe the changes in stress and strain under the action of excavation and unloading can help more accurately predict the long-term settlement of the foundation, thereby providing corresponding guidance on the settlement monitoring during the operation of the immersed tube tunnel and ensuring the tunnel safety. Yan (2003) [32] used the results of triaxial tests combined with the Dafalias bounding surface framework and the state-dependent dilatancy sand model proposed by Li (2000) [33] to obtain the constitutive model of fully weathered granite. However, there are many model parameters, and there are 17 model parameters without considering the structural influence of weathered rock and small strain characteristics. Chiu (2003) studied and compared the constitutive models of unsaturated, compacted, weathered granite soil and believed that the elastoplastic constitutive model of unsaturated soil proposed by Alonso et al. (1990) is more suitable for unsaturated, compacted, weathered granite soil after modification. On the basis of summarizing many research reports and experimental documents in Hong Kong, To (2008) [34] used the unified model of clay and sand proposed by Yu [25] to present a

practical constitutive model for remodeling fully weathered rock. This model can reflect the critical state theory and the phase transformation of sand and can better represent the main mechanical properties of remolded, fully weathered granite.

All the above models are based on the test results of weathered rocks in their natural state and do not take the strain-softening characteristics of weathered granites exposed to water into account. Therefore, it is necessary to develop a strain-softening model suitable for both natural and saturated weathered granite.

For the convenience of studying the problem, this paper employs the following model to study the strain-softening characteristics of the rock mass. The strain-softening process of the rock mass is presented in Figure 8. In this model, the elastic modulus of the rock mass before the peak strength is regarded as a constant quantity. In the figure, AB represents the elastic stage before the peak strength of weathered rock, and BC is the softening stage. In addition, the straight line parallel to AB is the unloading path during triaxial compression, and the distance from the point of intersection with the abscissa to the origin is the plastic internal variable ε_1^p .

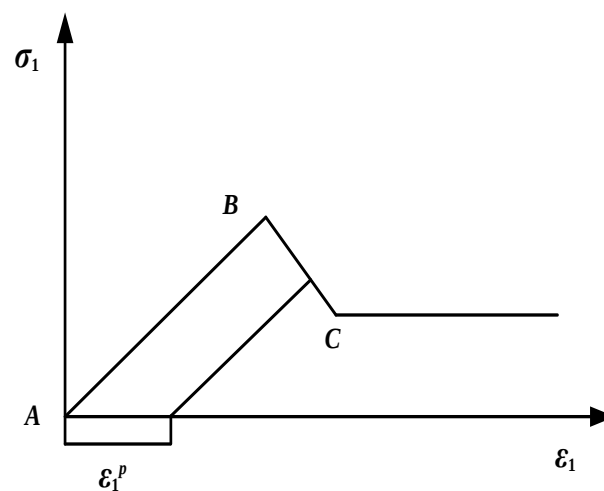


Figure 8. The stress–strain curve.

According to the above expression, without considering the elastoplastic coupling, Equation (2) can be obtained:

$$\varepsilon_1^p = \varepsilon_1 - \frac{\sigma_1}{E_0} \quad (2)$$

where ε_1^p is the plastic internal variable, ε_1 represents the axial strain, and E_0 indicates the elastic modulus before the peak.

Equation (2) can yield the value of the plastic internal variable at the peak residual stress, and the strain-softening parameter can be determined by this method, as expressed in Equation (3):

$$\varepsilon_{1r}^p = \varepsilon_{1r} - \frac{\sigma_{1r}}{E_0} \quad (3)$$

where ε_{1r}^p is the maximum plastic strain, ε_{1r} indicates the residual strain of the rock mass, and σ_{1r} denotes the residual stress on the rock mass.

Equations (4) and (5) define the internal friction angle and the cohesive force, respectively:

$$\varphi = \begin{cases} \varphi_0 + \frac{\varepsilon_1^p}{\varepsilon_{1r} - \frac{\sigma_{1r}}{E_0}}, & 0 \leq \varepsilon_1^p \leq \varepsilon_{1r} - \frac{\sigma_{1r}}{E_0} \\ \varphi_r, & \varepsilon_1^p > \varepsilon_{1r} - \frac{\sigma_{1r}}{E_0} \end{cases} \quad (4)$$

$$c = \begin{cases} c_0 + \frac{\varepsilon_1^p - \varepsilon_{1r}^p}{\varepsilon_{1r} - \varepsilon_{1r}^p}, 0 \leq \varepsilon_1^p \leq \varepsilon_{1r} - \frac{\sigma_{1r}}{E_0} \\ c_r, \varepsilon_1^p > \varepsilon_{1r} - \frac{\sigma_{1r}}{E_0} \end{cases} \quad (5)$$

According to the Mohr–Coulomb strength criterion, after the stress on the rock mass reaches the peak value, the stress state satisfies Equation (6):

$$\sigma_1 = \frac{2c \cos \varphi}{1 - \sin \varphi} + \sigma_3 \frac{1 + \sin \varphi}{1 - \sin \varphi} \quad (6)$$

where σ_3 represents the confining pressure on the rock.

For the strain softening, substituting Equation (2) into Equations (4) and (5), respectively, yields Equations (7) and (8):

$$\varphi = \varphi_0 + \frac{\varepsilon_1 - \frac{\sigma_1}{E_0}}{\varepsilon_{1r} - \frac{\sigma_{1r}}{E_0}} (\varphi_r - \varphi_0) \quad (7)$$

$$c = c_0 + \frac{\varepsilon_1 - \frac{\sigma_1}{E_0}}{\varepsilon_{1r} - \frac{\sigma_{1r}}{E_0}} (c_r - c_0) \quad (8)$$

Taking the partial derivative of Equations (7) and (8) with respect to the principal axial strain yields Equations (9) and (10), respectively:

$$\frac{\partial \varphi}{\partial \varepsilon_1} = \frac{1 - \frac{E_p}{E_0}}{\varepsilon_{1r} - \frac{\sigma_{1r}}{E_0}} (\varphi_r - \varphi_0) \quad (9)$$

$$\frac{\partial c}{\partial \varepsilon_1} = \frac{1 - \frac{E_p}{E_0}}{\varepsilon_{1r} - \frac{\sigma_{1r}}{E_0}} (c_r - c_0) \quad (10)$$

where E_p is the deformation modulus of the weathered rock in the softening stage after reaching the peak stress.

Taking the partial derivative of Equation (6) with respect to the principal axial strain yields Equation (11):

$$\frac{\partial \varphi}{\partial \varepsilon_1} = \frac{2 \cos \varphi \frac{\partial c}{\partial \varepsilon_1}}{1 - \sin \varphi} + \frac{[2\sigma_3 \cos \varphi + 2c(1 - \sin \varphi)] \frac{\partial \varphi}{\partial \varepsilon_1}}{(1 - \sin \varphi)^2} \quad (11)$$

Finally, the deformation modulus of the weathered rock in the softening stage after reaching the peak stress can be obtained by substituting Equations (9) and (10) into Equation (11):

$$E_p = \frac{2 \cos \varphi (1 - \sin \varphi) E_0 (c_r - c_0) + 2[\sigma_3 \cos \varphi + c(1 - \sin \varphi)] E_0 (\varphi_r - \varphi_0)}{(1 - \sin \varphi)^2 (E_0 \varepsilon_{1r} - \sigma_{1r}) + 2 \cos \varphi (1 - \sin \varphi) (c_r - c_0) + 2[\sigma_3 \cos \varphi + c(1 - \sin \varphi)] (\varphi_r - \varphi_0)} \quad (12)$$

4.2. Validation of Model

This study first takes finding the post-peak stress–strain curve of a fully weathered rock sample under a confining pressure of 500 kPa as an example to verify the developed model. To this end, we obtain the elastic modulus of the weathered rock sample before the peak (E_0), defined as the ratio of the axial stress at the peak to the axial strain at peak, and substitute it into Equation (3) along with the residual stress on the rock mass and the residual strain of the rock mass; then, the ε_{1r}^p of the weathered rock sample at the residual strength point can be calculated. Then, from substituting these data into Equations (4) and (5), it can be concluded that a corresponding c and φ can be obtained for each given ε_1^p . Next, Equation (6) calculates σ_1 in the strain-softening stage, and, finally, Equation (3) gives ε_1 . This work selects a total of 18 data points according to the test results.

On the basis of the one-to-one correspondence of the relevant quantities in Table 4, the strain-softening stress–strain curve of the strongly weathered rock can be determined, as plotted in Figure 9. The drawing process of the stress–strain curve of the rock sample is shown in Figure 10.

Table 4. The softening parameters of the fully weathered rock (SA-1).

p (kPa)	ε_1^p (%)	φ (°)	c (kPa)	σ_1 (kPa)	ε_1 (%)
500	0	18.6	39.08	202.04	1.87
	1.55	19.5	38.05	250.48	3.87
	3.1	20.4	36.98	271.46	5.61
	4.65	21.3	35.98	283.29	7.27
	6.2	22.2	34.94	291.45	8.90
	7.75	23.1	33.93	297.78	10.51
	9.3	24	33.01	303.20	12.11
	10.85	24.9	32.02	306.79	13.69
	12.4	25.8	31.21	307.63	15.25
	13.95	26.7	30.20	306.64	16.79
	15.5	27.6	29.38	305.65	18.33
	17.05	28.5	28.59	303.75	19.86
	18.6	29.4	27.99	302.00	21.40
	20.15	30.3	27.40	300.12	22.93
	21.7	31.2	26.91	298.22	24.46
	23.25	32.1	26.52	296.63	26.00
	24.8	33	26.48	294.56	27.53
	26.35	33.9	25.03	293.00	29.06

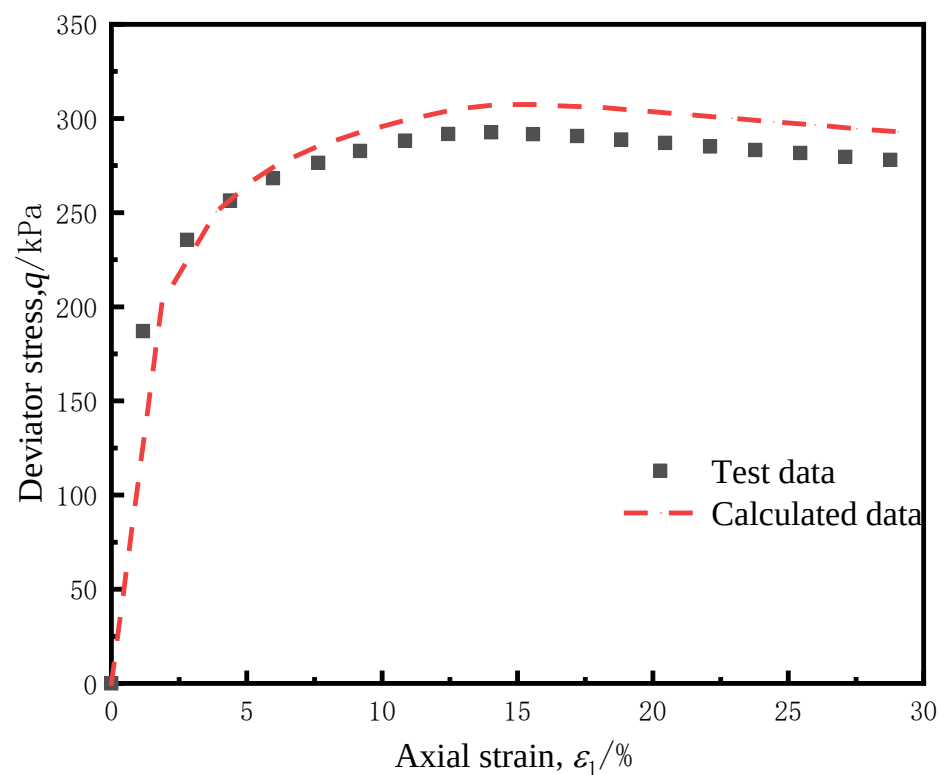


Figure 9. The calculated stress–strain curve fitted to the test data.

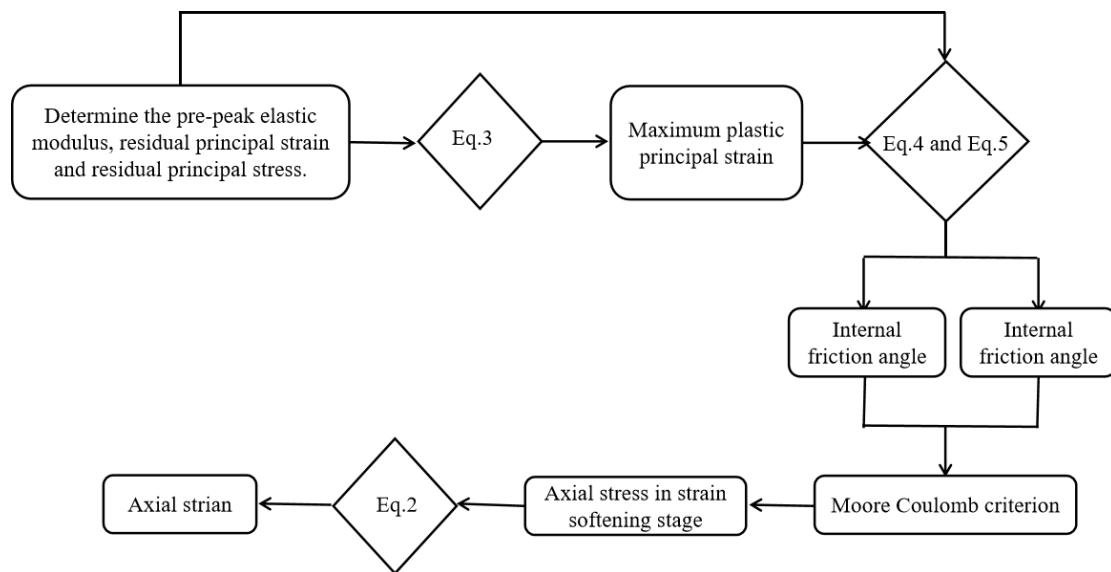


Figure 10. Stress–strain curve flow chart.

In the same way, the above method can be utilized to calculate the strain-softening parameters of the other fully weathered granites under a confining pressure of 500 kPa and those of the sandy weathered granites and fragmented weathered granites under a confining pressure of 600 and 680 kPa, respectively. Figure 11a–c represents the models fitted to each group of the experimental data. Except for the individual samples, the changing trend of the stress–strain curves of the weathered granites determined by this model is consistent with the measured data. The calculated results have a high degree of fit to the test results, and the dispersion is small (the goodness of fit R^2 of all samples is greater than 0.9). In addition, this paper employs the experimental data of Pang [35], Zhao [27], and He [36] to further verify the accuracy of the model, as depicted in Figure 11d. The calculated stress–strain curve of the weathered granite well agrees with the test data, indicating that the proposed model offers appropriate predictions.

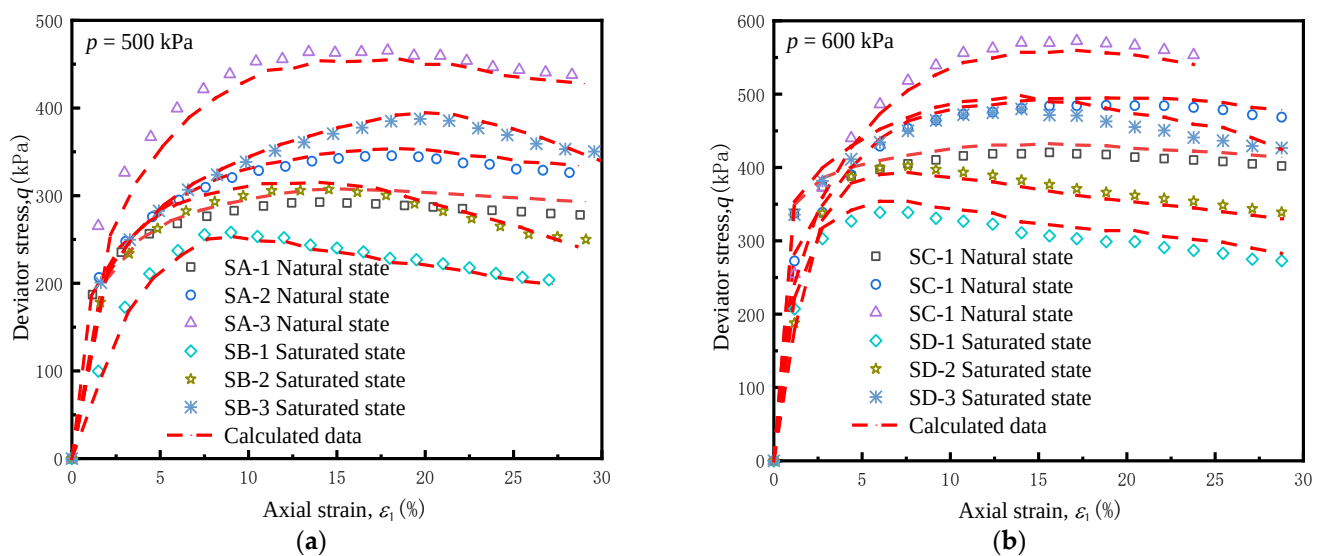


Figure 11. Cont.

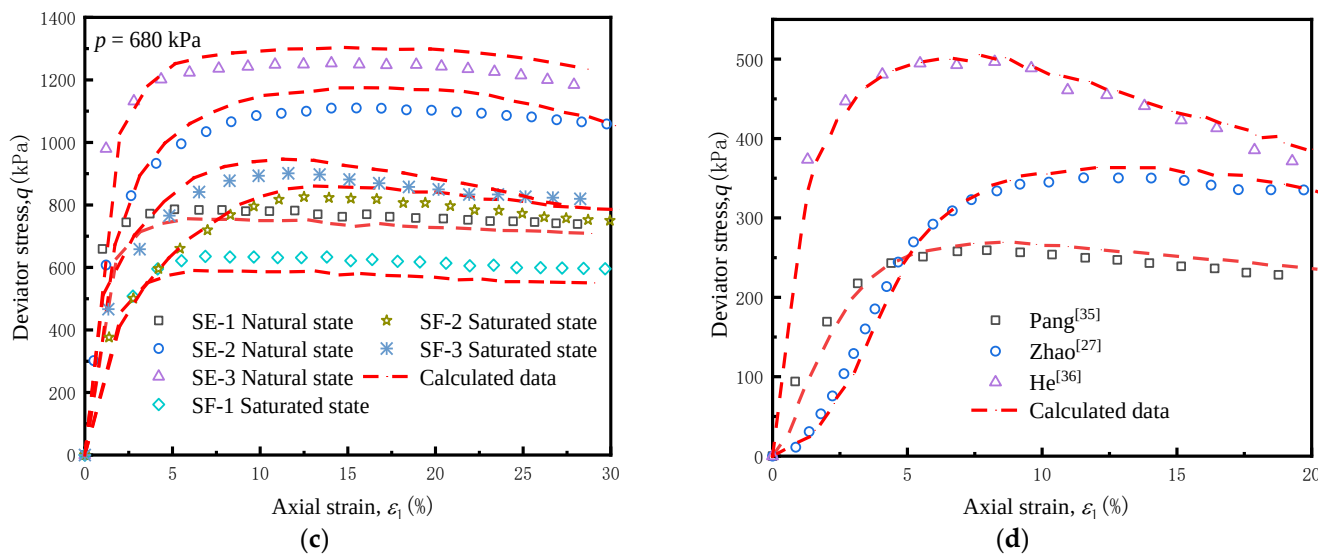


Figure 11. The calculated stress–strain curves of the weathered granite: (a) Fully weathered granites; (b) Sandy weathered granites; (c) Fragmented weathered granites; (d) Comparison between the measured and estimated values by the proposed model in Pang (2011), Zhao (2005), and He (2015).

5. Conclusions

This paper conducted a series of indoor undrained triaxial shear tests to examine stress and strain development of weathered granite in its natural and saturated states. To this end, the changes in the mechanical properties of the weathered granite exposed to water were analyzed, and the influence of the different consolidation conditions on the stress–strain curve of the weathered granite was discussed. In addition, a strain-softening model suitable for the natural and saturated states of weathered granite was developed to analyze the measured axial strain. From the above results and discussion, the following conclusions can be drawn:

1. The stress–strain curve of the weathered granite in its natural state can be roughly divided into three stages. In the initial stage, which happens at an axial strain of lower than 10%, 8%, and 5% for the fully weathered granite, the sandy weathered granite, and the fragmented weathered granite, respectively, the shear stress on the specimen soars with the axial strain; however, the slope of the stress–strain curve and thus the growth rate of the shear stress decline as the axial strain enlarges. After the sample reaches the peak stress, which happens at an axial strain of higher than 16%, 17%, and 12% for the fully weathered granite, the sandy weathered granite, and the fragmented weathered granite, respectively, the shear stress on the rock decreases with the axial strain, implying a particular strain-softening trend.
2. The stress–strain curve of the weathered granite in the saturated state is divided into two stages. Before the rock reaches its peak strength, the shear stress soars approximately linearly with the axial strain. When the weathered granite reaches its peak strength, it undergoes noticeable strain softening; in other words, the shear stress plummets with the axial strain.
3. Comparing the test results obtained in the natural and saturated states of the weathered granite reveals that the peak strength of the weathered granite decreases dramatically after exposure to water, and its corresponding peak strain is affected.
4. In actual engineering, weathered rock masses are often under deviator stress consolidation rather than isotropic consolidation. Therefore, studying the mechanical behavior of the weathered rocks under deviator stress consolidation is of more practical significance and theoretical value. The softening degree of the weathered granite varies as the consolidation mode changes and decreases to a certain extent as the shear stress applied by the deviator stress consolidation enlarges.

5. In the initial stages of the loading, shear shrinkage occurs since the pore water pressure increases; later, as the axial strain continues to increase, the rock shows a trend of shear dilatation until it reaches a critical state. The axial strain required for the shear stress to reach the peak value is always greater than that required for the dilatancy to occur.
6. We also established an empirical model describing the strain softening of weathered granite by utilizing the internal cohesion and the internal friction angle; the model suits weathered granite in natural and saturated states.

The proposed model provides valuable guidance on describing the stress–strain characteristics of weathered granite exposed to water. However, the model developed herein is derived based on the continuous simplification of the intermediate process. Thus, there are problems such as directly treating the rock as an ideal elastic substance and ignoring the elastoplastic coupling during the rock compression. These shortcomings will be comprehensively addressed in a future study to enhance the accuracy of the model for the strain softening of weathered rock. The influence of confining pressure on the stress–strain relationship of weathered granite will also be examined since it remarkably impacts on the mechanical properties of weathered granite.

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