

Study on strength and deformation characteristics of sandy mudstone based on triaxial unloading test

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Abstract. To achieve the strength and deformation characteristics of sandy mudstone under the unloading condition, a triaxial unloading test was performed on a group of sandy mudstone taken from the diversion tunnel of a hydropower station. The results show that the stress-strain curve slope of sandy mudstone increases suddenly at the moment of unloading confining pressure, and there is no significant decline in the whole test. There is usually only a whole shear failure surface in the samples damaged under low initial unloading confining pressure while those damaged under high one develop tensile fracture. The introduction of semilog method helps to solve the problem that it's difficult to get the peak intensity of sandy mudstone directly based on the variation characteristics of the stress-strain curve. From the initial stage of unloading to the damage of the samples, the reduced percentage of sandy mudstone deformation modulus is positively correlated with initial unloading confining pressure. The decrease rate of deformation modulus and increase rate of axial strain of sandy mudstone are both mutate under destructive confining pressure. The research results can provide an useful reference to research on the mechanical properties of similar soft rocks.

1. Introduction

With the rapid development of infrastructure construction and the advancement of Western Development in China, "More, longer, bigger and deeper" become the general trend of tunnel engineering. A large number of deep-buried long tunnel projects have been launched. Especially the big long tunnels for water conservancy and hydropower, highway and railway develop unprecedentedly. More and more projects face the problem of constructing underground caverns in the weak rock mass^[1]. Research has shown that soft rocks' mechanical properties are significantly different from hard rocks as engineering rock mass, which should be given much attention.

The triaxial test is one of the primary ones for determining geotechnical strength parameters, and the accurate geotechnical strength parameters thus acquired is the basis of solving related geotechnical theories and engineering problems^[2,3,4]. To provide construction advice for a hydropower station's diversion tunnel which goes through the sandy mudstone layer, samples of the sandy mudstone are taken specially to do triaxial unloading test, whose strength and deformation characteristics are studied.

2. Test conditions and test methods

The samples come from the diversion tunnel of a hydropower station in Western China, with a height of 100mm and a diameter of 50mm. Tests were done on the RMT-150C rock mechanics test system (as shown in Fig.1), and the temperature of the laboratory maintains at $20\pm 1^\circ\text{C}$ in the process of test.





Figure 1. RMT-150C rock mechanics test system

The triaxial unloading test methods adopted are as follows:

Firstly, use stress control mode, exerting $\sigma_1 = \sigma_3$ to predetermined value (10, 20, 30 MPa) gradually under the condition of hydrostatic pressure with loading rate 0.05 MPa/s.

Secondly, continue to adopt stress control mode, keep σ_3 constant and gradually increase σ_1 to 80% of the ultimate compressive strength under the same confining pressure at the loading rate of 0.05 MPa/s. Make sure the stress level of σ_1 is more than the uniaxial compressive strength and less than the triaxial compressive strength under corresponding confining pressure.

Lastly, carry on adopting stress control mode and reduce σ_3 gradually at the rate of 0.05 MPa/s while keeping σ_1 constant until the sample is damaged.

3. Stress-strain curve and failure characteristics of samples

The stress-strain curve of sandy mudstone under different initial unloading confining pressure is in Fig.2.

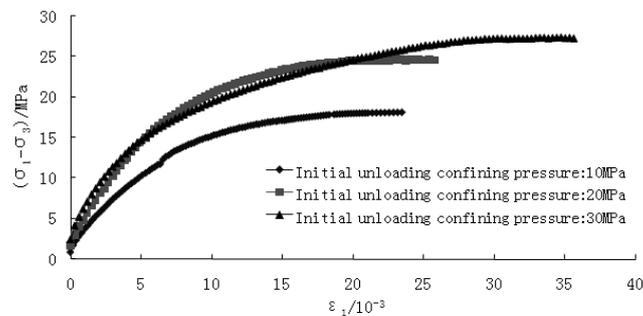


Figure 2. Stress-strain curves of sandy mudstone with triaxial unloading test

Fig.2 shows that the stress-strain curve slope of the sample increases suddenly in the instant of unloading confining pressure, which showed that the growth rate of axial strain decreases suddenly at the moment of unloading confining pressure, and this phenomenon is especially evident under lower initial unloading confining pressure. The analysis shows that this is because the higher the confining pressure is, the greater the constraints on the lateral expansion of the rock becomes. The sample enters destruction state gradually with the deviator stress ($\sigma_1 - \sigma_3$) increasing, a small change in deviator stress can cause great axial strain, and there is no distinct decline period on the stress-strain curve throughout the whole test, the sample shows significant strain hardening characteristics.

Fig.3 shows the failure pattern photos and sketch of the crack of sandy mudstone samples under different initial unloading confining pressure.

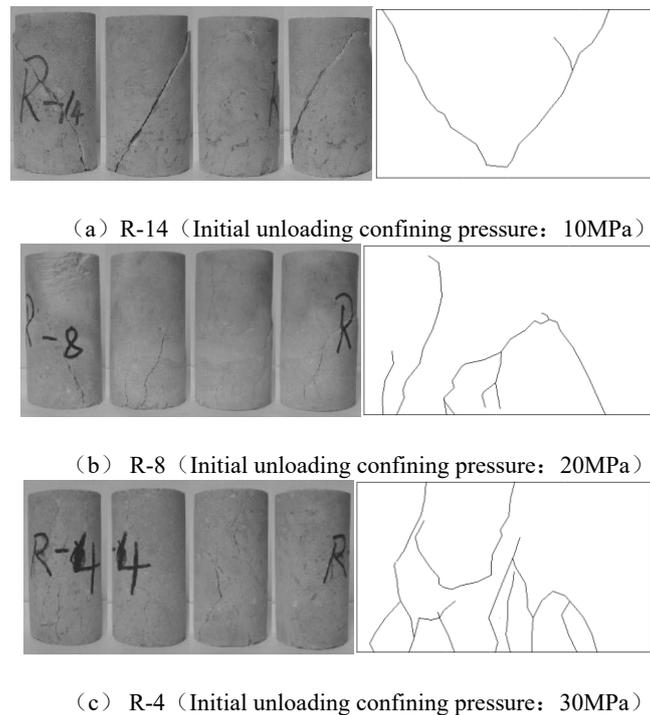


Figure 3. Failure pattern photos and sketch of the crack of sandy mudstone samples with triaxial unloading test

As shown in Fig. 3, although the stress-strain curve shows no significant decline, there is obvious damage in the sample taken from the testing machine. The sample remains a relatively complete cylinder form after the destruction and does not look fragmented like hard rock. Shear failure occurs in the sample under lower initial unloading confining pressure, and there is only a whole shear plane in the sample and no evident tensional fracture. With the increase of initial unloading confining pressure, lateral unloading degree of the sample increases, and tensional fractures produced in the direction of the maximum principal stress increase, with gradually increasing the degree of fragmentation.

4. Analysis of strength characteristics

Based on above analysis, it can be seen that after the destruction of the sample, the stress-strain curve shows no significant decline. Therefore, it is impossible to determine the peak intensity of the sample directly based on variation features of the stress-strain curve. Tu et al.^[5] proposed that when determining the peak intensity of an enormous outwash deposits based on large-scale triaxial test results, “when there is no distinct peak intensity, it should be the axial stress value when the axial strain is 15%”. However, many soft rock test results show that the plastic deformation of soft rock increases as the confining pressure increases. Therefore, it is obviously unreasonable to adopt the stress value at the same axial strain level as the sample’s peak intensity under different confining pressure. Meanwhile, You^[6] analyses that confining pressure determines the bearing capacity of the sample in the process of plastic deformation, namely it keeps carrying axial stress through friction and its bearing capacity doesn’t decrease with the increase of axial deformation. So, when the strain is maximum, it’s not right to choose the stress value as the sample’s peak intensity either.

To acquire the exact peak intensity of sandy mudstone in the triaxial unloading test, the semilog method which is often used in geo-technique triaxial and shear test data processing is introduced here after many trials. Fig.4 shows the σ_3 -lg ϵ_1 relation curve of the samples.

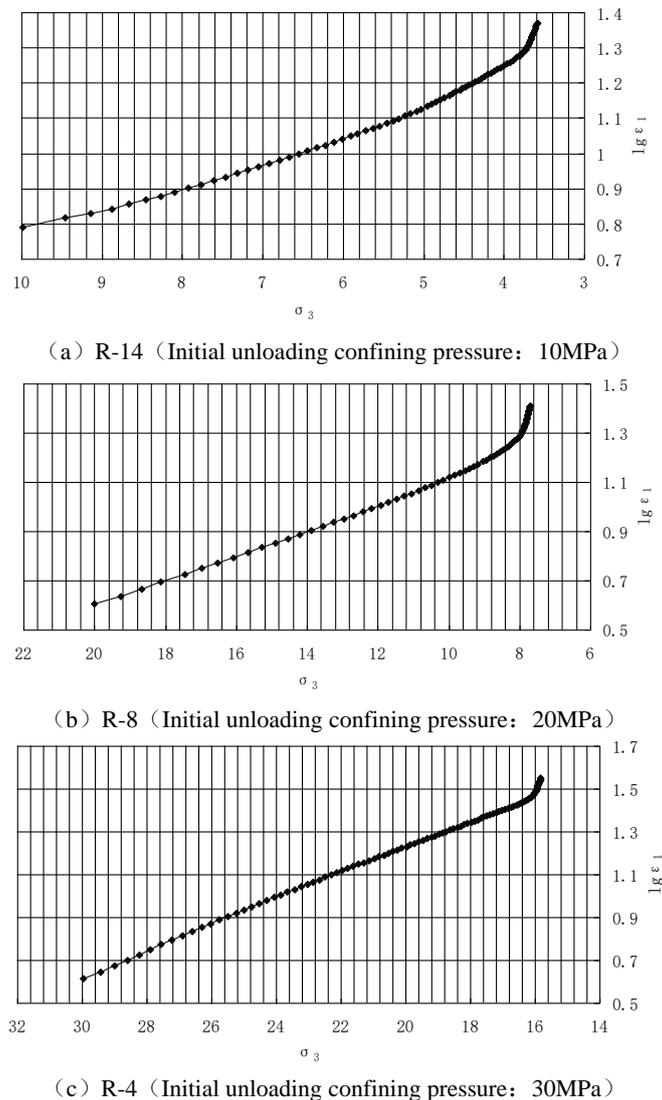


Figure 4. σ_3 - $\lg \varepsilon_1$ relation curve of sandy mudstone with triaxial unloading test

As can be seen in Fig. 4, there is an evident inflexion on the σ_3 - $\lg \varepsilon_1$ relation curve of sandy mudstone with the triaxial unloading test, which divides the curve into approximately two straight lines.

(1) The stage of slow rise: the sample is not yet destroyed. Before the unloading confining pressure decreases to the certain range of value, $\lg \varepsilon_1$ gradually increases at a basically constant rate. This shows that the axial strain of the sample increases at a constant rate during this period, but the sample shows no evident damage.

(2) The stage of quick rise: the shear failure surface of the sample expands quickly. When the confining pressure unloading reaches the certain value, $\lg \varepsilon_1$ increases sharply in a short time and the slope of σ_3 - $\lg \varepsilon_1$ relation curve increases rapidly, which shows that the sample was already destroyed then. After that, the axial strain of the sample increases quickly as the confining pressure declines.

Based on the above analysis, the demarcation point of the slow rise and quick rise corresponds to is the peak intensity of the sample. As is regulated in the reference^[7], the stress value that the inflection corresponds to is the peak intensity of the sample. Table 1 shows the peak intensity of different samples.

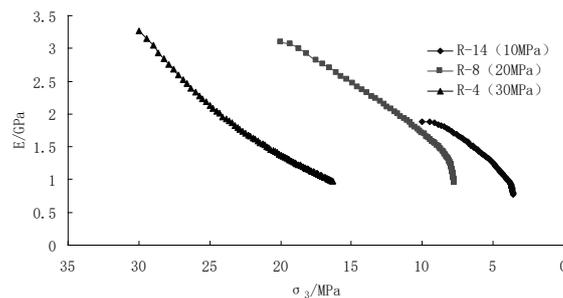
Table 1. Peak intensity of sandy mudstone with triaxial unloading test

Initial unloading confining pressure [MPa]	Axial strain [MPa]	Destroy confining pressure [MPa]	Peak intensity ($\sigma_1 - \sigma_3$) [MPa]
10	20	3.80	16.20
20	30	8.26	21.74
30	40	16.50	23.50

5. Analysis of deformation characteristics

5.1 The Relationship Between Deformation Modulus and Confining Pressure

Fig.5 shows the relationship between deformation modulus and the confining pressure of the samples during unloading. As can be seen in the picture, the deformation modulus of the rock declines gradually as the confining pressure declines during unloading. When the initial unloading confining pressure is relatively low, the variation range of deformation modulus relatively small in the initial period of unloading confining pressure, when the confining pressure decrease to destructive confining pressure, the deformation modulus declines sharply, and an obvious inflection occurs on the curve. When the initial unloading confining pressure is relatively high, the deformation modulus shows an obvious downtrend in the initial period of unloading, and the curve shows obvious non-linear characteristic.

**Figure 5.** Deformation modulus-confining pressure relation curve during unloading

To study the relationship between deformation modulus and initial unloading confining pressure of the samples from the initial stage of unloading to the time when the yield failure occurs, the statistics about the deformation modulus of the samples at initial unloading and destruction stage are shown in Table 2. As can be seen from the table, the higher the initial unloading confining pressure is, the more the deformation modulus declines during failure of the samples. The relation between the two is as shown in Fig.6. Based on linear fitting analysis:

$$\Delta E = 0.9665\sigma_3 + 39.17 \quad (1)$$

Where ΔE represents the declining percentage of deformation modulus, σ_3 represents the initial unloading confining pressure.

As can be seen in Fig.6, with the increase of initial unloading confining pressure, the declining percentage of deformation modulus from initial unloading stage to the time when the sample yield failure occurs increases linearly.

Table 2. Variation of Deformation Modulus in Unloading Process

Initial unloading confining pressure [MPa]	Initial deformation modulus [GPa]	Deformation modulus when destruction [GPa]	Decline percentage of deformation modulus [%]
10	1.88	0.94	50.00

20	3.08	1.35	56.17
30	3.26	1.00	69.33

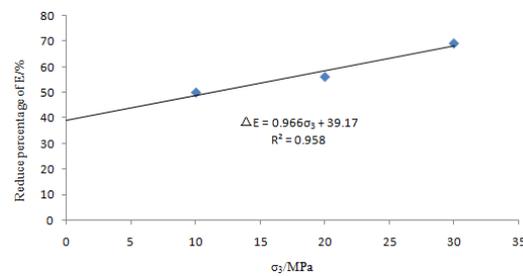


Figure 6. Relation curve of declining percentage of deformation modulus and initial unloading confining

5.2 The Relationship Between Axial Strain and Confining Pressure

Fig.7 shows the relationship between axial strain and confining pressure during unloading process. The increase rate of the sample's axial strain is relatively small at the initial unloading stage, and the increase rate of axial strain rises sharply as confining pressure decreases to destructive confining pressure, then the strain-confining pressure relation curve is almost horizontal. The higher the initial unloading confining pressure is, the bigger the axial strain of the sample is.

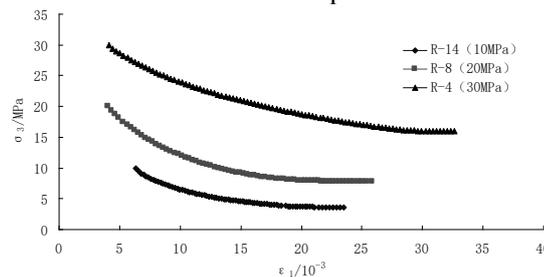


Figure 7. Axial strain-confining pressure relation curve

6. Conclusion

Through analyzing the test results of sandy mudstone under triaxial unloading test, the conclusions are as follows:

(1) There is no obvious decline in the strain-stress curve of sandy mudstone, which shows evident features of strain hardening. So, it is impossible to acquire the peak intensity of the sample directly based on the variation characteristics of the strain-stress curve.

(2) The sample of sandy mudstone remains relatively complete after destruction. There is usually only a whole shear failure surface in the samples destroyed under lower initial unloading confining pressure while samples destroyed in higher initial unloading confining pressure develop tensional fractures.

(3) By introducing semilog method into the data analysis of triaxial unloading test, the peak intensity of the samples is determined conveniently through $\sigma_3 - \lg \varepsilon_1$ relation curve.

(4) From the initial stage of unloading to the destruction of the sample, the declining percentage of sandy mudstone's deformation modulus increases linearly with the rise of initial unloading confining pressure. Meanwhile, both the declining rate of its deformation modulus and the increase rate of axial strain increase suddenly when the confining pressure reduces to destructive confining pressure.

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