EXPERIMENTAL STUDY ON THE SOFTENING CHARACTERISTICS OF ARGILLACEOUS SLATE WITH WATER

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ABSTRACT

Because the stratification of argillaceous slate developed well, the anisotropy is obvious and it is easy to soften when encountering water, in the excavation, tunnel is easy to cause large deformation and collapse. In order to understand the softening mechanism of argillaceous slate in water and mechanical anisotropy and to provide reference for solving practical engineering problems, in this paper, introducing an argillaceous slate highway tunnel project in Zixi County of Jiangxi province. By preparing standard specimens in field sampling, the mineral composition analysis, water rational test and uniaxial compression test were carried out. The result shows: The main mineral composition of argillaceous slate is sericite, inclusion of a few chlorite, quartz and so on. This composition makes obvious characteristics of soft rock. The influence of hydration on the mechanical properties of argillaceous slate is large. With the increase of water content, the peak strength shows a downward trend, while the Poisson ratio shows the characteristics of slow growth. At the same time, the mechanical properties of argillaceous slate are obviously anisotropic by the direction of stratification plane. The failure modes of argillaceous slate mainly include axial tension, local shear failure and shear failure along the stratification plane.

KEYWORDS

Argillaceous Slate, Tunnel Surrounding Rock, Compression Test, Water Rationality, Mechanical Properties

INTRODUCTION

In recent years, the number of tunnel construction in our country is increasing, and various complicated geological environment emerge in endlessly. Argillaceous slate, as a kind of stratified rock, its joint surface developed well and is easy to be softened by water. At present, engineers and technicians know little about the deformation and failure mechanism of the rock. In the process of tunnel excavation, it is easy to cause large deformation, collapse and other disasters and cause great losses, which brings some difficulties to the tunnel construction. Many scholars at home and abroad have carried out many theoretical and experimental researches on layered rock. The results obtained are helpful to further study the mechanical properties and deformation mechanism of layered rock mass. In the field of theoretical research, some scholars have studied the constitutive model and failure prediction of slate. Zuo Qingjun etc al[1] based on the basic constitutive model in the existing Burgers creep, by introducing the water deterioration factor, established the visco elastic plastic creep constitutive equation of argillaceous slate considering water absorption, and divided the argillite creep into attenuation, steady state and accelerated creep three stages. Huang Shuling et al. [2] proposed a model of hardening and softening of layered rock composite materials, and described the strength and deformation anisotropy and progressive fracture (or slip) characteristics of these rock masses. Zhang Yujun et al. [3] ,thought the method of searching and trial calculation combing the empirical expression of the shear strength of layered rock mass varying with the direction of rock layer with the Mohr Coulomb criterion is used to predict the shear failure surface and orientation of slate, which is more in line with reality. In the field of experimental research,Yang Chunhe et al[4], by electron microscopy, X ray diffraction and other tests on slates, explained microscopically the softening mechanism of slate in water. It is considered that with the increase of soaking time, the capillary force and the surface tension between the mineral particles of slate decrease, and the cohesive force of the slate decreases. Fall M [5] studied the influence of interstitial water pressure on the strength of shaly shale by simulating the gas injection test. By three axial compression test, Nguyen T S et al[6-9] established the argillite constitutive model, and revealed the relationship between mechanical parameters of slate such as peak strength and elastic modulus and confining pressure, moisture content and jointed relationship, proof the slate rock has anisotropic mechanical characteristics, and proved that the slate rock mass has anisotropic mechanical characteristics. In the slate rock tunnel stability, Lisjak A et al[10,11], by using the numerical analysis software, for the excavation of slate tunnel with different stratification plane directions, carried out numerical analysis, explained the characteristics of stratification plane direction effecting on the stability of the tunnel. Su Zhendao [12], in the deformation and stress analysis of the tunnel lining, based on the field test of the argillite tunnel, he recommended that the radial grouting behind the lining of the tunnel should be taken to reduce the pressure of the lining so as to enhance the stability of surrounding rock. Although there are many researches on the engineering properties of slate, however, there are few studies on the physical and mechanical characteristics of argillaceous slate, and the results both theoretically and experimentally are very limited. In this article, for a highway tunnel project in Zixi County of Jiangxi, the mineral composition analysis, water rational test and uniaxial compression test of argillaceous slate are carried out. Furthermore, the mechanism of softening of argillaceous slate with water and its mechanical anisotropy are revealed. The physical and mechanical properties of argillaceous slate are established, which provides reference for engineering decision-making.

TEST OVERVIEW

Test equipment and method

The mineral composition analysis of argillaceous slate was carried out by D8ADVANCE X-ray diffractometer produced by Brook Company of Germany. The device can scan the sample at different angles and obtain the X ray diffraction pattern of different mineral components in the sample for analyzing the mineral composition of the sample. The scanning range of this experiment is 5°- 65°, and the scanning speed is 0.02 °/s. The water rational test of argillaceous slate includes water absorption test and expansion test and so on. The test equipment includes electronic scales, thermometer, drying box, vacuum pump etc. The specific test methods can refer to the "water conservancy and hydropower engineering rock test procedures” edited by the Yangtze River academy of Sciences [13], here is no longer described. The uniaxial compression test was carried out by use of a RMT-150 compression test machine, as is shown in Figure 1. The device has the advantages of simple operation, convenient loading and deformation controlling, high measuring accuracy, long continuous operation time, stable working performance and strong protection function and other advantages. It is widely used in a single three axial compression test of rock materials. In the test, the axial load is controlled by controlling the axial displacement; the axial deformation rate of the preset specimen is 0.002mm/s; the upper limit of axial displacement is set. After the axial load is started, the axial load is maintained until the specimen axial deformation reaches its preset upper limit or until the yielding failure of the argillaceous slate samples occurs, then the test is stopped. During the whole compression test, the experimental data are recorded automatically by the test system, and the fracture features and the failure modes of the argillaceous slate are observed and recorded by manual observation.

Fig. 1 - RMT-150 Compression Machine

Specimen preparation

The specimens used in the test are all argillaceous slates taken from the construction site of a highway tunnel in Zixi County of Jiangxi Province, as is shown in Figure 2. The weathering degree of argillaceous slate is different, and the degree of fracture development is different. In the field, a more complete block is selected. The maximum length of rock block is about 20cm. Because of the significant anisotropy of argillaceous slate, the drilling core sampling is respectively done in accordance with the stratification direction of vertical, 45°and parallel. The sample is a standard cylinder with a molding diameter of 50mm and a height of h of 100mm. In the process of specimen preparation, the roughness of the end face is controlled at about 0.005mm, and the axial direction is kept perpendicular to the radial direction. After the specimens were finished, selected the specimens with smooth surface, no obvious cracks and intact, studied the velocity of specimens using acoustic instrument to avoid the influence of the case of not dense or void in the test piece on the test result. Finally, covered with a layer of plastic wrap on the selected specimens and stored in the laboratory for test preparation.

Fig. 2 - Weathered argillaceous slate

EXPERIMENTAL RESULTS AND ANALYSIS

Mineral composition and water rationality test

Mineral composition analysis of argillaceous slate samples was carried out by using D8ADVANCE X- ray diffractometer, as shown in Figure 3. The mineral composition of argillaceous slate includes sericite, chlorite, quartz and a small amount of kaolinite and feldspar. The content of Sericite is the highest, which is 46.6%, which shows that it has the greatest influence on the engineering properties of argillaceous slate, followed by quartz and chlorite, and the content is about 20%. The analysis shows that the sericite intensity is low, and a loose and flaky structure, so that the argillaceous slate has the characteristics of water permeability, uneven and loose structure, which eventually leads that the strength of argillaceous slate becomes low and its stability becomes bad, and the properties of soft rock and schist are prominent.

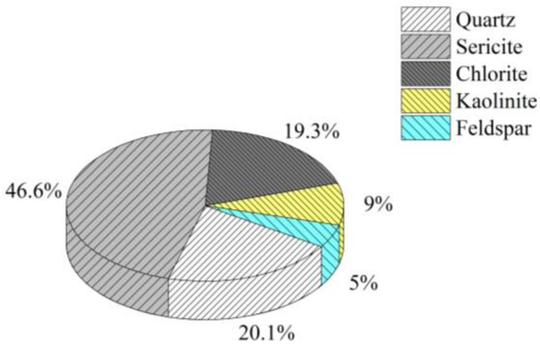


Fig.3 - Mineral composition of argillaceous slate

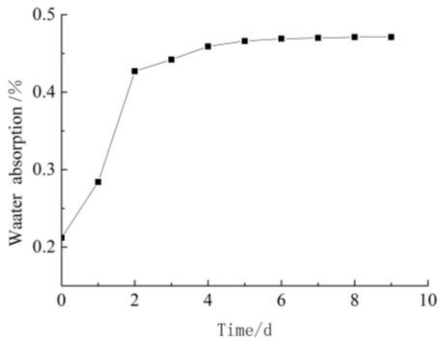


Fig.4 - The relationship between water absorption and time

The water rationality of argillaceous slate includes water absorption characteristics, swelling characteristics and disintegration characteristics. Through the field sampling, according to the standard, a group of specimens were prepared in the laboratory, and the corresponding tests were carried out. The results of water absorption test were shown in Figure 4. The swelling test results were shown in Table1.

Tab.1 - Test results of natural swelling of argillaceous slate

Specimen number	The angle between the stratification plane and the axial direction	Axial expansion value (mm)	Radial expansion value (mm)	Axial expansion ratio (%)	Radial expansion ratio (%)
1	90°	0.0025	0.0165	0.0035	0.0234
2	90°	0.0009	0.0515	0.0013	0.0789
3	0°	0.0635	0.0031	0.1387	0.0057
4	0°	0.1578	0.0198	0.1231	0.0329

The experimental results show that the water quantity of argillaceous slate under natural condition in the early immersion was proportional to the immersion time. In fourth days, with the growth of time, the natural water absorption rate showed a decreasing trend, and eventually stabilized, the water absorption rate remained at about 0.45%; the swelling deformation is affected by water and stratification plane structure, no matter the angle between the axial and stratification plane of the specimens are either 0°or 90°,the rate of expansion in the direction parallel to the stratification plane is always higher than that in the direction perpendicular to the stratification plane. The reason is that the contact area between clay minerals parallel to the stratification plane and water is larger, and it is easier to absorb water and expand. But water is difficult to enter the clay minerals between the stratification plane, and the expansion rate is smaller; in the expansion test of argillaceous slate, it is observed that the disintegration of argillaceous slate is related to the integrity and weathering degree of the sample. Relevant tests show that the higher the degree of fragmentation, the stronger the disintegration. In addition, under dry conditions, argillaceous slate is more likely to disintegrate and more rapidly disintegrate than in natural conditions.

Uniaxial compression test

Through the uniaxial compression test of argillaceous slate specimens under different stress and moisture content, the mechanical properties, such as deformation, strength and failure of argillaceous slate, are studied.

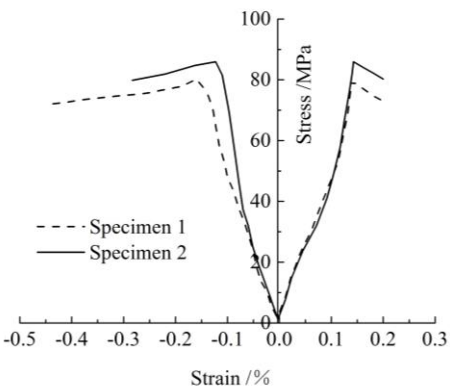
Deformation characteristics

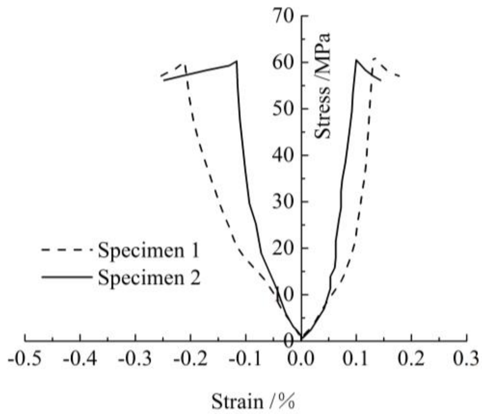
Uniaxial compression specimens were divided into 3 groups: axial direction perpendicular to stratification plane direction, 45° degrees with stratification plane direction and parallel stratification plane direction. Each group is made of 2 specimens. The specimen size of the uniaxial compression test is shown in Table 2, and the stress-strain curve obtained in the test is shown in Figure 5.

Tab.2 Specimen size of uniaxial compression test

Specimen number	0-1	0-2	45-1	45-2	90-1	90-2
Specimen height (mm)	98.3	97.9	96.4	97.6	97.9	98.2
Specimen diameter (mm)	48.7	49.3	49.7	46.1	47.4	47.2
Height diameter ratio	2.02	1.99	1.94	2.11	2.06	2.08

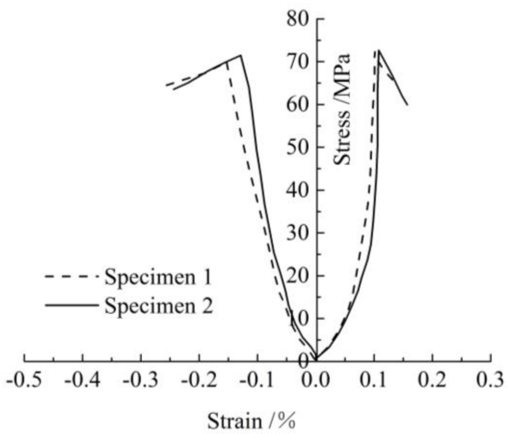
Note: the first number indicates the angle between the axis of the specimen and the stratification plane. The second numbers indicate the number of the specimen in the group. The following is the same as this.





(a) The stratification plane is perpendicular to the axial direction of the specimen

(b)The angle between the stratification plane and the axial direction of the specimen is 45°



(c) The stratification plane is parallel to the axial direction of the specimen

Fig.5 - The stress-strain curves of argillaceous slate under uniaxial compression

Figure 5 shows the stress-strain curves of the argillaceous slate under different working stress from the beginning of the loading to the stage of failure. It can be seen from the figure, the trend is quite similar, contains the specimen compression phase, elastic deformation and crack development stage and failure stage, but the magnitude of the peak reflects a different, the rate of deformation in each stage is obvious differences. The contrast analysis shows that: when the stratification plane perpendicular to the specimen axial, both the axial peak strain and lateral strain peak are at about 0.0015; while the stratification plane parallel to the specimen axial or 45°, the axial peak strain is greater 0.005 than lateral peak strain. It indicates that the strain has the characteristics of anisotropy significantly. In the compaction stage, nonlinear characteristics are exhibited, and the deformation rate is fast. The nonlinear characteristics are influenced by the fracture development of the argillaceous slate and the roughness of the end face of the specimen. The deformation of argillaceous slate develops from the elastic deformation stage to the fracture stage, showing the characteristics of elastic deformation, and the direct result of elastic deformation is the swelling deformation of its volume. In the failure stage of argillaceous slate specimens, axial deformation increases sharply and shows obvious brittle failure characteristics.

Strength characteristics

The uniaxial compression test results are shown in Table 3. It can be seen from the table that the uniaxial compressive strength of argillaceous slate is obviously affected by the dip angle of the stratification plane. When the argillaceous slate specimen axial is perpendicular to the rock stratification plane, the average value of the argillaceous slate compressive strength is 85.45MPa; it is the maximum value of the compressive strength of the test specimen into 3 groups. The failure mode is shear failure or splitting failure. When the angle between argillaceous slate specimen axial and the rock stratification plane is 45°, argillaceous slate compressive strength average value is 60.58MPa, it is the minimum value of the compressive strength of the test specimen into 3 groups. The specimen is sheared along the rock stratification plane. When the argillaceous slate specimen axial is parallel to the rock stratification plane, the average value of compressive strength of the argillaceous slate specimen is 73.84MPa, the compressive strength value is between that of the two groups test specimen mentioned above and the specimen appears to be in shear failure mode. Through further tests, it can be seen that, with the increase of stratification plane angle from 0°to 90°, the compressive strength and modulus of argillaceous slate changes similar to V type. The uniaxial compressive strength of argillaceous slate shows different characteristics of its mechanical properties in different directions, and it also shows that the rock is the most unfavorable state of force when the inclination of the stratification plane is close to 45°.

Tab.3 Results of uniaxial compression test

Number	Height (mm)	diameter (mm)	compressive strength (MPa)	average value (MPa)	elastic modulus (GPa)	average value (GPa)	Poisson ratio	failure modes and shear angles
90-1	98.3	48.7	86.04	85.45	32.25	33.22	0.22	shear failure
90-2	97.9	49.3	84.86		34.18		0.20	shear failure
45-1	96.4	49.7	64.44	60.58	25.31	25.00	0.18	A certain angle along the stratification plane
45-2	97.6	46.1	56.71		24.68		0.19	A certain angle along the stratification plane
0-1	97.9	47.4	74.12	73.84	28.48	26.82	0.23	vertical failure
0-2	98.2	47.2	73.56		25.15		0.25	vertical failure

Failure characteristics

The essence of argillaceous slate specimens from the beginning load to the final fracture is that, under external force, the gradual evolution process of generation, propagation and coalescence of the internal cracks. That is to say, rock failure is a macroscopic reflection of the accumulation of rock microstructure deformation. Figure 6 is the state of the specimen when it is broken.

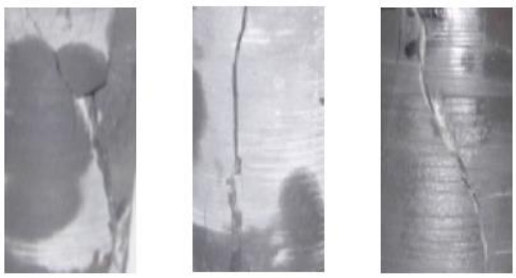


Fig. 6 - Failure modes of rock specimen

Through the observation of the failure state characteristics of argillaceous slate and other specimens in the test, the failure forms of argillaceous slate specimens can be simply divided into three types: Cracks are formed parallel to the axial direction when tensile failure occurs in the axial direction; comprehensive local shear and tensile failure modes simultaneously with lateral expansion phenomenon; the shear failure modes along the stratification plane. By analyzing the failure evolution process and failure modes of rock samples, the stress path in the course of rock force, as well as the influence of different loading factors on rock failure characteristics can be obtained.

Effect of water content on mechanical properties of argillaceous slate

The forming method of uniaxial compression test of argillaceous slate sample with different water content is the same as that of front uniaxial compression test specimen. The specimens of argillaceous slate are perpendicular to the stratification plane direction. A total of 7 specimens are made to study the influence of water content on the mechanical properties of argillaceous slate. The soaking time of argillaceous slate samples is respectively 0d, 1d, 2d, 4d, 8d, 16d and 32d. Table 4 is the results of uniaxial compression test of argillaceous slate after soaking. Figure 7 shows the relationship between the uniaxial compressive strength and the length of immersion time of argillaceous slate specimens.

Tab. 4 - Results of uniaxial compression test of argillaceous slate under different saturated time

Specimen number	Soaking time (d)	Water content (%)	elastic modulus (GPa)	compressive strength (MPa)	Poisson ratio
1	0	0.136	31.46	76.32	0.21
2	1	0.203	32.56	68.54	0..27
3	2	0.236	30.64	62.25	0.31
4	4	0.251	28.65	55.18	0.34
5	8	0.262	34.16	53.31	0.36
6	16	0.268	32.22	45.27	0.36
7	32	0.270	30.65	41.26	0.37

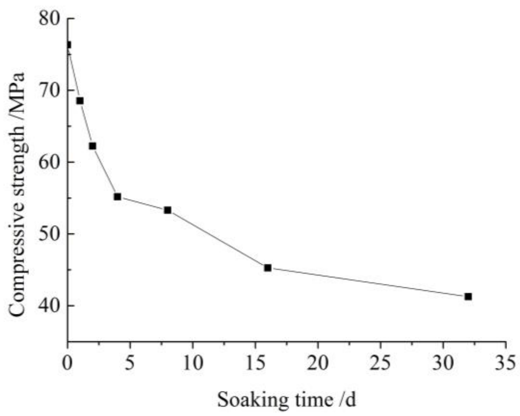


Fig. 7 - Relationship curves between strength and saturated time

Table 4 and Figure 7 shows: with the increase of argillaceous slate soaking time, the uniaxial compressive strength of argillaceous slate shows obvious decreasing trend; the decreasing rate is first fast and then slow; the variation law of modulus is discrete, while the Poisson ratio of argillaceous slate shows a trend of slow increase. In the natural water content state, the uniaxial compressive strength of argillaceous slate is 76.32MPa, and the uniaxial compressive strength is minimum when submerged 32d, and the value is 41.26MPa. The longer the soaking time of argillaceous slate, the more the uniaxial compressive strength decreases. In the 5 days before immersion, the decreasing rate of uniaxial compressive strength is fastest. Subsequently, the decreasing rate of its uniaxial compressive strength gradually slow down, and it was basically stable after 16d.The analysis shows that when argillaceous slate after immersion, due to physical and chemistry of water on the argillaceous slate, argillaceous slate itself and its inner friction angle decreases, the cohesion of clay decrease, which lead to argillaceous slate strength will produce large losses. With the increasing of soaking time of argillaceous slate specimens, the Poisson ratio shows a trend of slow increasing. It reflects the increasing ability of its lateral expansion deformation.

CONCLUSIONS

By testing on the mineral composition of argillaceous slate analysis, water rational characteristic and uniaxial compression, the microstructure of argillaceous slate, stress-strain characteristic and failure characteristics in different stratification plane and soaking time were studied. The conclusions are as follows:

(1) The argillaceous slate minerals used in the test are mainly sericite, followed by chlorite and quartz. Because the stability of sericite is poor, clay minerals are mixed between bedrock layers, it result obvious soft rock characteristics of argillaceous slate. Under the action of water, it is easy to expand, soften and even disintegrate. It has obvious water softening characteristics;

(2) The strength characteristics of argillaceous slate show the anisotropy with angle of the specimen axial direction and the stratification plane. In the original test scheme, the angle of the specimen axial direction and the stratification plane only 0°, 45 °and 90 °, the test state is less. However, taking into account the continuity of rock mechanical properties, some basic conclusions can be obtained.It changes similar to the V type with the increase of angle. When the shale specimen is perpendicular to the rock stratification plane, its compressive strength is the largest, and the fracture mode of the specimen is shear failure or splitting failure; In the three set specimen, when the angle between the axial direction and the stratification plane of the argillaceous slate specimen is 45°,the compressive strength is the minimum, and the specimen appears shear failure along the stratification plane. When the argillaceous slate specimens are axially parallel to the stratification plane, the compressive strength is between that of the above-mentioned specimens, showing a shear failure.

(3) Because of the physical and chemical effects of water on argillaceous slate, the mechanical properties and deformation characteristics of shale are obviously changed. With the increase of soaking time, the friction angle of clay rock itself and its clay layer decreases and cohesive force decreases, and then the compressive strength shows obvious decrease trend. When the soaking time is more than 15 days, the compressive strength reduction is almost 50%.With the increase of water content, the Poisson ratio of argillaceous slate samples shows a trend of slow increase, which indicates that the ability of lateral expansion deformation increases gradually under the influence of water.

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REFERENCES

[1] Zuo Q J, Wu L, Li B, Lu Z L, Yuan Q, Chen F,et al. Creeping properties of water-rich argillaceous slate surrounding tunnel[J]. Chinese Journal of Rock Mechanics and Engineering, 2015(10):2047-2056, in Chinese.

[2] Huang S L, Xu J S, Jing X L, Wu A J,et al. Study of layered rock mass composite model based on characteristics of structural plane and its application[J].Chinese Journal of Rock Mechanics and Engineering. 2010(04):743-756, in Chinese.

[3] Zhang Y J, Liu Y P, et al. Anisotropy of shear strength of layered rocks and determination of shear failure plane [J]. Rock and soil Mechanics, 2001(03):254-257, in Chinese.

[4] Yang C H, Mao H J, Wang X C, Li X H, Liu J W, et al. Study on variation of microstructure and mechanical properties of water- weakening slates [J]. Rock and Soil Mechanics, 2005(12):2090-2098, in Chinese.

[5] Fall M. Simulation of a gas injection test in a layered argillaceous rock[C]// International Conference on Computational Geomechanics, Comgeo II. 2011.

[6] Nguyen T S, Le A D. Development of a constitutive model for a bedded argillaceous rock from triaxial and true triaxial tests1[J]. Canadian Geotechnical Journal, 2015, 52(8):1072-1086.

[7] Gao C Y, Xu J, LI Z H, Deng J H, et al. Experimental study of anisotropic ally mechanical characteristics of sandy slate in Xuefeng mountain tunnel [J]. Rock and Soil Mechanics.2011 (05):1360-1364, in Chinese.

[8] Wang M, Zhu Z M, Feng R Q, et al. Experimental study on failure behaviors of cracked rocks around tunnels under true triaxial unloading [J]. Journal of China Coal Society. 2015(02):278-285, in Chinese.

[9] Wang L, Liu Z Y, et al. Triaxial Compression Test of weakly cemented mudstone [J]. Journal of Yangtze River Scientific Research Institute.2016 (08):86-90+95, in Chinese.

[10] Lisjak A, Garitte B, Grasselli G, et al. The excavation of a circular tunnel in a bedded argillaceous rock (Opalinus Clay): Short-term rock mass response and FDEM numerical analysis [J]. Tunnelling and Underground Space Technology incorporating Trenchless Technology Research, 2015, 45(45):227-248.

[11] Tan X, Fu H L, Chen C, Zhao M H, Liu Y S, et al. Numerical simulation analysis of tunnel in rock-mass[J]. Journal of Railway Science and Engineering.2016 (06):1108-1113, in Chinese.

[12] Su Z D, Luo J J, et al. Experimental study and prediction on large section tunnel construction deformation of surrounding rock in soft ground [J].Chinese Journal of Rock Mechanics and Engineering.2016 (S2):4029-4039, in Chinese.

[13] Yangtze River Water Resources Commission, Yangtze Academy of Sciences. Water conservancy and hydropower engineering rock test gauge (JGJ SL264-2001) [S]. Beijing: China Water Conservancy and Hydropower Press, 2001, in Chinese.