Advances on the mechanical behaviors of anisotropic shale rock mass

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Abstract

As the geological environment of shale rock mass is complexity, the mechanical properties of it is easily affected by the presence of the environment, rock components, bedding planes and human activities. Thus, there exists a high degree of complexity and uncertainty on the strength anisotropy of rock mass which has brought great difficulties for shale gas exploitation. In order to analyze the anisotropic of shale rock mass mechanical properties comprehensively, this paper summarized the research methods and conclusions of rock mass anisotropy, summed up the law of compressive strength changes with the bedding dip of shale rock mass, failure mechanism of it under uniaxial and triaxial compression, and deformation parameters of it changes with bedding dip under different confining pressure based on the extensive literature survey, from both the theoretical and experimental aspects. This study can help researchers to make a more comprehensive understanding on the strength and mechanical properties of shale rock mass, and provide some guidance for engineering practice.

Keywords

Shale rock, bedding, mechanical properties, anisotropy, compression test.

1. Introduction

Shale gas is an unconventional energy, which is accumulated in low porosity and low permeability, dark organic-rich shale or clay shale-carbon system, it is considered to be the ideal successor to conventional oil and natural gas, which is widely distributed mining potential [1]. In our country, shale gas resources are very rich, but the mining technology is still infancy. In recent years, with the increase of energy demand, China has gradually increased exploration and development pace of the shale gas. Since forming conditions, reservoir space, seepage law and the own characteristics of the development model, especially for low porosity reservoirs and ultra-low matrix permeability and other factors, which have brought great difficulties and challenges to the mining of it. In order to achieve efficient exploitation of shale gas, anisotropy test of shale rock mass is urgently needed to analyzed the mechanical properties under different inclinations, to form basic theory and technical measures of shale gas fracturing technology adapting our country, which has important practical significance to accelerate the exploration and development of shale gas.

Scholars have done numerous of researches on anisotropy of shale rock mass, and made a lot of achievements. However, these findings were too messy, therefore, through research large number of documents, this article summarized the compressive strength and mechanical properties of rock anisotropy from theoretical research, laboratory experiments and numerical simulation, summed up the compression failure mechanism of shale rock mass under uniaxial and triaxial compression, and the deformation parameters change with bedding dip under different confining pressure. The study has a certain reference function on analyzing anisotropic properties of shale rock mass, and can provide some guidance for engineering practice.

2. theoretical research

1860s, Jeager proposed frail surface theory, and established a jointed rock strength model based on Mohr-Coulomb criterion, which used two Mohr-Coulomb equation to describe the shear failure of joint rock mass and intact rock mass. Hoek-Brown strength criterion gives surface structure the meaning of experimental parameters and fixed its shear strength by introducing empirical constants m and s, which explains the effects of surface structure, and has been widely used in some projects [2, 3]. Hangzhou Li et al. [4-8] discussed anisotropic strength characteristics of rock under plane strain conditions based on strain softening model and ubiquitous - joint model, established an anisotropic strength criterion of jointed rock mass under complex stress condition, studied anisotropic properties of strength, stress, strain, deformation and failure mechanisms of layered rock mass and verified it through numerical analysis and compression test. Guike Zhang [9] studied the fracture network generation technology, macroscopic equivalent deformation parameters and the calculation of shear strength parameters, orthotropic shear yield criterion of anisotropy rock systematically, and recommended a new nonlinear elastic constitutive relation to compute structural plane deformation. Xu Lei et al. [10] based on anisotropic layered rock mass deformation and strength characteristics, McLamore & Gray strength criterion, spreaded the isotropic Drucker-Prager strength criterion by changing the parameters relationship between Mohr-Coulomb strength criterion and Drucker-Prager strength criterion, applied to the layered rock mass, and established anisotropic constitutive model of the layered rock mass. Yang Tianhong [11] proposed a new method which simplified the calculation of the anisotropic model based on FEM software in two coordinate systems (base coordinate system and the auxiliary coordinate system). Wang Bingjun [12] simulated the layered rock foundation by regarding it as a semi-infinite transversely isotropic media, took the ratio of elasticity parallel and perpendicular to the direction of the level to characterize the degree of rock anisotropy, studied the influence of anisotropy of elastic modulus, shear modulus and Poisson's ratio parallel and perpendicular to the level of rock on a single rectangular crack stress intensity factor (SIF) orthogonal to the level and the interaction between the two crack using dual boundary element method. Li Han, Mi Jian [13] combinated the theory and practical, analyzed the mechanical properties of rock in-depth by using Multi-layer structure theory, and developed non-linear method of calculation to describe the model of rock. H. Saroglou [14] calculated impact of bedding dip on strength anisotropy of intact rock specimen under different loads through introducing new parameters.

Most of these studies established a new relationship and empirical formulas of strength to analyze anisotropy of rock strength based on the theory of strength and intensity criteria.

2.1 Theoretical Model

Strain softening model

Strain softening model is special form of Mohr-Coulomb model [7], this model is mainly used to simulate the strain-softening behavior after the external load exceeds the yield limit of rock mass. The strain is mainly elastic strain ε_e in the elastic stage, after exceed the yield strength, plastic strain ε_p produced, strain becomes $\varepsilon_e + \varepsilon_p$, after the generating of plastic strain, the cohesion c, and internal friction angle ϕ of corresponding unit will change with the plastic strain (shear strain and tensile strain) changes, which is $\bar{c} = f_c\left(\bar{\varepsilon}^p\right)$, $\bar{\phi} = f_\phi\left(\bar{\varepsilon}^p\right)$, the equivalent plastic strain is as formula (1)[7]:

$$\bar{\varepsilon}^p = \sqrt{[(\varepsilon_1{}^p - \varepsilon_m{}^p)^2 + (\varepsilon_2{}^p - \varepsilon_m{}^p)^2 + (\varepsilon_3{}^p - \varepsilon_m{}^p)^2]/2} \tag{1}$$

Where

$$\varepsilon_m{}^p = (\varepsilon_1{}^p + \varepsilon_2{}^p + \varepsilon_3{}^p)/3 \tag{2}$$

Where c, ϕ is obtained by inversion based on laboratory and field tests, the yield criterion of the model is the same as the Mohr-Coulomb model, on yield surface, the failure point of shear stress is determined by the non-associated flow criterion, and the failure point of tensile stress is determined by the associated flow criterion.

Ubiquitous - joint model

Ubiquitous-joint model is an extension of Mohr-Coulomb model, it includes bedding planes in specific direction of Mohr-Coulomb. After the reduction rock strength, rock mass, joint or both of them could be first damaged. Where shear failure using the non-associated flow rule, tensile failure using the associated flow rule. Tendency bedding plane is defined by Cartesian coordinate components, x, y, z represents the whole coordinate, x', y', z' represents the local coordinate. Stress relations between generalized coordinates and local coordinates is as formula (3) [7]:

$$\sigma' = C^T \sigma C \tag{3}$$

Where

$$C = \begin{bmatrix} \cos(x',x)\cos(y',y)\cos(z',z) \\ \cos(y',x)\cos(y',y)\cos(y',z) \\ \cos(z',x)\cos(z',y)\cos(z',z) \end{bmatrix}$$

Yield criterion of joint surface is shown in Figure 1. According to Mohr-Coulomb criterion, under the local coordinate, yield envelope AB represents fs = 0; tensile failure envelope BC indicates ft = 0, and they are satisfied the following formula (4):

$$\begin{cases} f^s = \tau + \sigma_3' \tan\phi_j - c_j \\ f^t = \sigma_3' - \sigma_j^t \\ \sigma_{j_{\max}}^t = c_j / \tan\phi_j \end{cases} \tag{4}$$

Where: ϕ_j - internal friction angle, c_j - cohesion, σ_j^t - tensile strength.

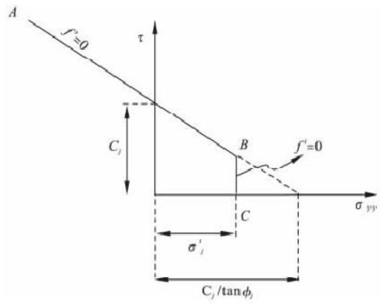


Figure 1 yield criterion of weak joint surface

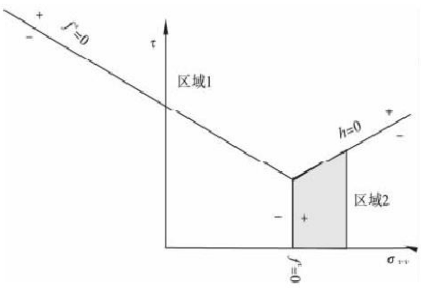


Figure 2 flow rule of Joints weak surface of Ubiquitous - joint model

Figure 2 is flow rule of joint weak surface, the figure shows that when the rock mass stress state in the stable region ("+"), it appears linearly elastic state and does not require amendment of plastic, while in the yield area ("-"), it need to be amended according to the association (non-associated) flow rule, which can be expressed as a function as the form:

$$h = \tau - \tau_j^p - d_j^p (\sigma_3' - \sigma_j') \tag{5}$$

Stress state in area 1 in figure 2 indicates the weak joint enter into the shear failure, then flow rule and shear potential function gs are used to pull stress point to the envelope fs = 0; the stress state of zone 2 represents weak joint surface enter into tensile failure; then pull-out function gt is needed to pull the stress point to the envelope ft = 0.

2.2 Mechanical response of joint surface

The joint surface of the specimen will generate normal stress and tangential stress, the value of the stress will change with the joint angle changing, stress on joint plane can be expressed as[15] shown in Figure 1:

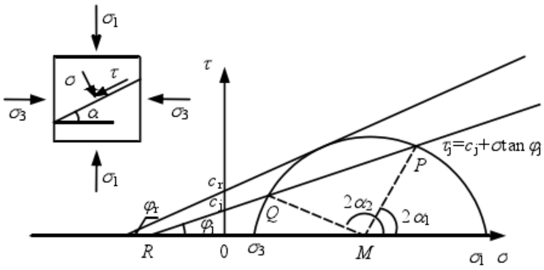
$$\begin{cases} \sigma = (\sigma_1 + \sigma_3)/2 + (\sigma_1 - \sigma_3)\cos(2\alpha)/2 \\ (\sigma_1 - \sigma_3)\sin(2\alpha)/2 \end{cases} \tag{6}$$

According to Coulomb, intensity curves RQP joint plane can be expressed as:

$$S_s = c_j + \sigma \tan\phi_j \tag{7}$$

Where: ϕ_j - internal friction angle, c_j - cohesion.

When $\alpha = \alpha_1$ or $\alpha = \alpha_2$, that is point Q and P of intensity curves RQP, it represents that the stress of joint plane is just in the limit equilibrium state; when $\alpha < \alpha_1$ or $\alpha > \alpha_2$, the stress points of moore is under the intensity curve RQP of joint plane, the shear stress of joint surfaces is less than the shear strength, sliding failure along it will not occur; when $\alpha_1 < \alpha < \alpha_2$, the stress points of moore is above the intensity curve RQP, the shear stress of joint surfaces is bigger than the shear strength, sliding failure along it will occur.



It can be seen, when the joint angle $\alpha_1 < \alpha < \alpha_2$, the destruction of jointed rock mass mainly controled by the joint surface; when the joint angle $\alpha < \alpha_1$ or $\alpha > \alpha_2$, the destruction of jointed rock mass is almost unaffected by joint plane, but controlled by the rock strength.

In figure 1, $\angle RPM = 2\alpha_1 - \phi_j$, equation (8) can be obtained as follow[15]:

$$\tau_m \sin(2\alpha - \phi_j) = (\sigma_m + c_j \cot\phi_j)\sin\phi_j \tag{8}$$

Where: σ_m - average stress, $\sigma_m = (\sigma_1 + \sigma_3)/2$; τ_m - maximum shear stress, $\tau_m = (\sigma_1 - \sigma_3)/2$.

It can be obtained from the formula (8):

$$\begin{cases} 2\alpha_1 = \phi_j + \sin^{-1}\left(\dfrac{\sigma_m + c_j \cot\phi_j}{\tau_m}\sin\phi_j\right) \\ 2\alpha_2 = \pi + \phi_j - \sin^{-1}\left(\dfrac{\sigma_m + c_j \cot\phi_j}{\tau_m}\sin\phi_j\right) \end{cases} \tag{9}$$

Formula (9) shows that the critical angle when jointed rock mass destruction occurs along the joint is determined by the strength parameter and stress state of the joint plane.

3. Experimental Study

3.1 SEM and acoustic experiments

Scanning electron microscope

The anisotropy of shale rock is a very complex mechanical problems, it closely related to its internal structure. Therefore, in order to further study the anisotropy mechanism of shale rock, it is necessary to study from meso and micro conception. Since the magnification range of SEM is 20-20000, it can enlarge both the larger area only 20 times to observe the object comprehensively and the subtle part to 20,000 times to observe the object in a more detailed and in-depth way, Therefore, the scanning electron microscope is widely used in studying the microstructure of shale rock mass[16].

In 2008, Yan Xiaobing, et al.[17-20] measured the content and the distribution of minerals and observed rock mass deformation using a microscope. Jiang Quan [21] described transverse isotropic characteristics in the structure olumnar jointed rock mass on the basis of scanning electron microscopy (SEM). Chai Zhaoyun [22] analyzed the expansion anisotropy and the formation mechanism of argillaceous rock through the swelling test and SEM test. Quan Gao et al [23] studied the surface morphology, microstructure and chemical composition of the shale rock mass by using scanning electron microscopy and X-ray, and measured the compressive strength and tensile strength anisotropy of rock mass through experiment and noninvasive acoustic testing.

The researches above observed the microstructure and material composition of rock mass and analyzed its effects on the mechanical properties anisotropic of shale rock mass by using scanning electron microscopy.

Acoustic experiments

Through the joint specimen acoustic wave velocity test, Sun Xushu [24] noted that acoustic velocity of intact specimen and the joint specimens are normally distributed, and there is a certain discrete through the joint specimen acoustic wave velocity test. For joint specimens, through changing the position of the sensor to make the sound waves pass through the different angles of incidence joints, compared with the intact specimens, sonic through different incident angles of joints attenuate in varying degrees, and the degree of attenuation increases linearly with increasing of angle incidence. Wang Jiaxing [25] used acoustic field test to analyze the macroscopic physical and mechanical anisotropy of quartz and mica schist, the result showed that the velocity of it eppears obvious anisotropy, the velocity is the maximum along foliation direction, the minimum velocity perpendicular to foliation direction, the value of velocity in other directions between both of them, the velocity of specimen was significantly increased from the upper to the lower and anisotropy index showed a decreasing trend. Wu Qiuhong et al [26] inferred that there eixsted a advantage direction of a fractured surfaces in rock through longitudinal wave velocity tests on granite specimen, the P-wave velocity along the normal direction is lower than other directions. Tang Jie et al [27] studied the crack evolution anisotropic properties of low porosity shale rock mass and mudstone of Dongying region, obtained ultrasonic response characteristics under conditions of isotropic shale, and analyzed the influence of stress amplitude shale acoustic velocity and anisotropy. Shang Deng et al [28] did sonic experiments of the rock samples, measured the velocity parallel and perpendicular to bedding dip, and described anisotropic of cross bedding.

The achievement above analyzed the macroscopic physical and mechanical anisotropy of rock mass by studying the velocity propagation in the specimen, distribution and attenuation of sound waves after pass through the specimens.

3.2 Compression test

Uniaxial compression test

Since the uniaxial compression test is simple and its low cost, accurate mechanics parameters, such as compressive strength, elastic model, Poisson's ratio can be obtain by uniaxial experiments, thus, it has been widely used in mechanical properties studies of rock mass. Researchers have done a lot of work in this area and acheived a large number of results. Li Zheng-rong et al[29-32] studied the compressive strength, elastic modulus and the mean average Poisson's ratio, static and dynamic elastic modulus and Poisson's ratio of static and dynamic of gray slate and shale rock mass in different bedding directions under the load by uniaxial compression tests, and analyzed the effects of bedding on mechanical parameters of shale rock mass. And drawn deformation and strength anisotropy curve change with the bedding angle changes, and researched the influence mechanism of bedding dip change on rock strength anisotropy and deformation and failure. Liu Aihua [33] choosed a rock samples with apparent bedding structure, accomplished conventional mechanical parameters uniaxial compression experiments, simulated the failure process of rock mass tensile, compressive tests under different conditions inclination, and analyzed numerical simulation results and experimental results comparatively. Liu Shengli [34] discussed the mechanical properties of the sample anisotropy and deformation characteristics under different stress state by uniaxial compressive and indirect tensile test specimens disk, it reveals the mechanics mechanisms of different deformation and fracture. Jiang Quan [21] clarified the strength of columnar jointed rock mass anisotropy by uniaxial compression test on core sampling of different direction and rock point load test. Sun Xushu et al. [15, 25, 35] inferred that the existence of bedding planes made uniaxial compressive strength and deformation modulus of specimen decreased, the above parameters are U-shaped with joint angle changes, the minimum of the parameters appears in the range of 30 °- 60 °; the main failure mode of the sample is tensile failure, the destruction characterize controled by foliation and the loading direction. Zhangqiong Wang [36, 37]studied the deformation parameters anisotropy and failure mechanism under different bedding dip of Wudang Group schist through using uniaxial compression test, and analyzed deformation parameters anisotropic of the samples in natural state and saturated comparatively. Wu Chongzhou [38] studied the creep law anisotropy of brittle layer greenschist specimen by uniaxial compression test. Zhang Yongze et al. [19, 20] carried out uniaxial compression tests for Longmaxi shale, analyzed anisotropy of mechanical parameters and damage characteristics based on different shale bedding planes. And concluded the mainly three kinds of failure modes: tension failure parallel to the bedding planes, Shear failure along the bedding planes, tension failure through the bedding surface. Mohamed A. Ismael [39] studied the relationship between the degree of anisotropy and the minimum of anisotropy parameters, and predict the the minimum of anisotropy parameter by uniaxial compression test.

The researches above analyzed the influence of bedding planes on the mechanical parameters of shale rock mass, derived that the specimen uniaxial compressive strength and modulus of deformation presenting a U-shaped with change of joint angle, and the minimum of specimen parameters appears in the range of 30 °-60 °. Analyzed the influence mechanism of bedding dip change on the strength anisotropic and deformation and destruction of rock mass by plotting anisotropy curve of deformation and strength with bedding angle change.

Triaxial compression test

Because the high cost and difficulties in operation of true triaxial compression test, the conventional triaxial testing was used to instead of it to study the strength and deformation anisotropic behavior of rock mass, and the effects of confining pressure on the mechanical parameters. In 2007, the Bao Hongtao [40] used the triaxial compression test, combined with the experience of rock parameter estimation method to study controlled mechanical parameters of slate Tunnel, given a more reasonable physical and mechanical parameters for numerical simulation and provided a reliable basis for it. Hai-Ning Liu et al. [41, 42] carried out a true triaxial physical simulation test of jointed rock mass to study the fracture, stress and failure mechanism under complex stress state of rock mass, and the stress - strain relationships and strength characteristics under main triaxial stress of different directions. Wang Rubin et al. [1, 15, 24, 43-48] studied the impacts of stratification on deformation characteristics, strength characteristics and parameters of rock by triaxial compression test, obtained strength and deformation parameters of metamorphic tuff perpendicular and parallel to bedding planes under different confining pressures, analyzed failure modes and mechanisms of the sample under triaxial compression, summed up the variation of rock strength with the angle between weak structural surface and a principal stress load, and used anisotropic index to evaluate the degree of phyllite anisotropy quantitatively. Gatelier, N et al. [49-51] did conventional triaxial loading and unloading test of rock samples, and concluded that loading direction has a great influence on the destruction mechanism of the sample, meanwhile, with the increasing of confining pressure, anisotropy decreased significantly. Dawei Hu et al [52] studied the effect of intrinsic anisotropy, water content and interaction on anisotropy of saturated clay containing bedding plane, described its intrinsic anisotropy of mechanical behavior through discrete thermal method, analyzed the anisotropic elastic modulus, plasticity and damage evolution, and applied the predictive model to triaxial test of shale with different bedding dip and water content. Yukai Fu et al [53] introduced shear ratio evolution equation model of critical state and validated it by triaxial compression tests, accordingly, derived that the model can describe the inherent anisotropy of weak sedimentary rocks.

Researches above mainly through triaxial compression tests to study the influence of stratification on deformation characteristics, strength characteristics and parameters of rock, and to analyze the failure modes and mechanisms of the sample under the triaxial compression.

3.3 Numerical Simulation

Using zoning classification macroscopic mechanical parameters simulation method, and combining theoretical ideas "Representative unit", Liu Jie [54] simulated the anisotropy and analyzed the macro-mechanical parameters on the two-mica schist of Danba hydropower station, and obtained macroscopic mechanical parameters as well as the anisotropic characteristics variation in different bedding dip of it. Guosong Feng [55] used the method of numerical analysis to authenticate the guidelines applied in existing results and the obtained critical confining pressure. Liu Xuekun [7] analyzed the peak strength and the stress-strain relationship of multiple sets of samples comparatively, and studied the influence of the size and existing of joint on anisotropic mechanical properties of the rock. Li Yumei [56] established a three-dimensional finite element modeling of shale horizontal well about fracture initiation, researched sensitivity of elasticity anisotropic and stress anisotropy on hydraulic fracture initiation. Gong Shuxian [57] combined the laboratory and numerical simulation to analyze the impact of structure, strength and deformation characteristics and the anisotropy of the layered rock material on the rock stability. Jia Shanpo [32] analyzed the characteristics of layered rock mass deformation and failure by model test, discussed the influence of changes in inclination and laminated on rock mass strength and damage, and used numerical simulation to verify the results. Xiao Dongkun [58] studied the strength and failure characteristics of non-penetrating intermittent jointed rock mass by numerical simulation, summarized the geometry distribution, the influence of stress conditions on failure modes, strength characteristics of joint, the results showed that it has a good consistency with the results of physical tests. Based on laboratory test data under the multi-angle load, Cui Zhen et al [59] discussed the applicability of the discrete element method, synthesis rock method and continuum method based on jointed rock mass in the description of the applicability of anisotropic rock mechanics numerical simulation methods, and analyzed mechanical properties anisotropic problem of quartz mica schist. Hu Zhiming[60] studied the strength anisotropy of jointed rock mass from the macroscopic at different angle of joints under different confining pressure by applying of numerical methods. Xuxu Yang et al [61] studied the effects of joint inclination on rock mass strength, parameters and failure modes when under pressure and there is no support pressure. And analyzed the mechanical properties of jointed rock masses by numerical simulation.

The studies above using numerical simulation to analyze the failure process at different rock bedding dip under tensile, compressive strength test, to explain the failure mechanism of jointed rock mass from the force, deformation and failure, to study the macroscopic mechanical parameters and anisotropy variation in different inclination of rock mass, and the results of simulation and experiment were analyzed comparatively, and found that the results were in great consistent.

4. Main conclusion

(1)The stress - strain curve of shale belongs to class Ⅱ, there is no significant compaction stage, after reaching peak intensity, specimen damage occurs suddenly, it showes strong brittleness.

(2)Uniaxial compressive strength curve is approximately U-shaped, it obtains the maximum value when θ near at 0 °or 90 °and when θ near at 30° the shale uniaxial compressive strength reaches the minimum value, there are many reasons account for its anisotropy, from the micro level, it is because the different development degree of micro-cracks, from the view of macro, it is mainly due to its different failure modes.

(3) Uniaxial compression: θ= 0°, tensioning splitting failure along bedding; θ=30°, shear slippage along bedding; θ= 60°, shear failure penetrating bedding and along bedding; θ= 90°, tension splitting failure penetrating bedding. Triaxial compression: θ= 0°, conjugate shear failure penetrating bedding; θ=30°, shear slippage along bedding; θ= 60° and 90°, shear failure penetrating bedding.

(4) Rock strength anisotropy changed because of the presence of confining pressure, with the increasing of confining pressure, rock strength increased, but the anisotropy coefficient and the degree of anisotropic properties decreased, the rock transformed from anisotropic to isotropic.

(5) The elastic modulus of shale increased with the increasing of confining pressure, but the rate of increasing gradually decreased, the increasing rate of the elastic modulus decreased with bedding dip increasing under the same confining pressure, when θ= 60° or 90°, the increasing of confining pressure almost has no impact on the elasticity modulus of shale rock mass. With the increasing of confining pressure, Poisson's ratio is increased when θ= 0° or 30°, while decreased when θ= 60° or 90 °.

5. Suggestions and Prospects

(1) Because of the complexity and diversity of bedding rock mass, in the course of numerical analysis of rock, some assumptions simplicity were made about the nature bedding planes, thus, it cannot reflect the actual situation of rock engineering completely, which has a great effect on the strength and mechanical behavior of rock anisotropy analysis. Therefore, more rock engineering examples were required to verify the results of the study and revised it, only in this way will it services for the construction better.

(2) Since there are many factors exist, such as the rock specimen is too small, sliced disturbance, the single observation section and uniaxial loading restrictions, which to a certain extent, will reduce the reliability of scanning electron microscope results.

(3) The existing of sample collection, processing and human factors in the progress of experiment, to some extent, have led the experimental results some differences. At the same time, regional sampling results have also made the experiment results one-sidedness.

(4) Since the mechanical properties of the rock mass is affected by many factors, whether using the test method or numerical simulation method, it is difficult to achieve accurate and effective quantitative analysis for all the factors within the scope of the study. Therefore many factors will be taken into account together, it may be the focus of future research directions.

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