Research Article

Study on Stability and Plastic Zone Distribution of Tunnel with Thin Carbonaceous Slate at Different Dip Angles

Jin Zhang,1 Chuanhao Xi,1 Qian Zhang,2 and Mengxue Wang1

1College of Civil Engineering, Qingdao University of Technology, Qingdao 26033, China
2Beijing Key Laboratory for Precise Mining of Intergrown Energy and Resources, China University of Mining and Technology, Beijing 100083, China

Correspondence should be addressed to Jin Zhang; zhangjin@qut.edu.cn

Received 13 April 2021; Accepted 26 April 2021; Published 10 May 2021

Academic Editor: Qingxiang Meng

Copyright © 2021 Jin Zhang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Carbonaceous slate is heterogeneous and anisotropic, which has a great influence on the stability of tunnel. In this paper, by means of laboratory test, field measurement, and numerical simulation, the surrounding rock stability and plastic zone distribution characteristics of the carbonaceous slate tunnel at different intersection angles are analyzed. First, combined with the Haibaluo tunnel project, Brazilian splitting and uniaxial compression tests of jointed carbonaceous slate are performed. The test results show that the tensile strength of carbonaceous slate is related to joint dip angle. When the joint angle is 0°, the tensile strength is the largest and decreases with the increase of the joint angle. The uniaxial strength of rock decreases first and then increases. Based on the discrete fracture network (DFN) technology, a calculation model is established. The calculation results show that the maximum displacement is 0.45 m, when the dip angle of the surrounding rock joint is 45°. The field measurement also shows that the dip angle of the surrounding rock joint has an important influence on the distribution of the plastic zone. When the joint dip angle is 45°, the plastic zone develops most strongly.

1. Introduction

The stability of surrounding rock plays a decisive role in the safe excavation of tunnel. In the process of tunnel excavation, when the surrounding rock is disturbed, the stress will redistribute and plastic zone would be expansion. The strength of rock mass in the plastic zone decrease obviously, the fracture expands, and the stability of surrounding rock is weak [1]. When the joints are relatively developed, the plastic sliding phenomenon is easy to occur. Previous engineering experience shows that the size of the plastic zone will have a significant impact on the stability of the tunnel and the difficulty of the support. When the area of plastic zone is larger, the stability of surrounding rock is worse, and the difficulty of roadway support is greater.

Numerical analysis has become a more and more common method in the study of surrounding rock stability. In the study by Xiang and Feng [2] based on the assumption of homogeneous isotropic ideal elastic-plastic soil, a theoretical method is proposed to predict the secondary stress field and the corresponding potential plastic zone caused by tunnel excavation near the pile foundation. Taking the calculation results as an example, the theoretical results are compared with the corresponding numerical simulation results to demonstrate the development characteristics of the plastic zone of the tunnel. Lu et al. [3] calculated the elastic-plastic stress and strain of circular tunnel in rock mass controlled by Mohr Coulomb failure criterion. The results show that the stress, strain, and failure zone in the surrounding rock are related not only to the transverse in situ stress but also to the axial in situ stress. Massinas and Sakellariou [4] provide an opportunity to quickly and accurately calculate the plastic zone and stress distribution around a circular tunnel. By using different support pressure values, tunnel designers can easily evaluate the feasibility of different design schemes, such as shotcrete shell and tunnel boring machine support pressure. Behnam et al. [5] discussed the calculation of the plastic zone of the surrounding rock of a circular tunnel under
nonhydrostatic conditions, which satisfies the Hoek Brown failure criterion, and reviewed the calculation of the plastic zone and displacement of the surrounding rock under hydrostatic conditions. Li et al. [6–8] used the method of discrete element numerical simulation to analyze the distribution characteristics of in situ stress, the control effect of support on plastic zone, and the distribution characteristics of plastic zone under water rock coupling. In the study by Annan et al. [9], in order to solve the problem of surrounding rock stability, the displacement field, stress field, and plastic zone in the construction process of CRD method were analyzed by using the method of numerical simulation and field monitoring. Shi et al. [10] derived the principal stress distribution function around a circular tunnel from elastoplastic mechanics, calculated the boundary and radius of plastic zone under different strength criteria. The results show that the variation law of plastic zone around circular tunnel under different strength criteria has the following commonalities: first, with the increase of lateral pressure coefficient, the shape of plastic zone presents the variation law of “circle ellipse butterfly.” With the increase of lateral pressure coefficient, the radius of plastic zone presents exponential distribution. When the radius of plastic zone is infinite, the eigenvalues are different. In the study by Wu et al. [11–13], through induction, theoretical analysis, numerical calculation, and field measurement, the deformation characteristics, plastic zone distribution, and support control measures of large deformation tunnel in soft rock are studied. Hu et al. [14] used numerical simulation to study the phenomenon of large deformation of weak surrounding rock. At present, with the development of science and technology, some advanced numerical simulation methods for geotechnical engineering modeling are more and more common. For example, Meng et al. [15] used heterogeneous material modeling for digital image processing. At the same time, many experts also use the indoor test and similar material simulation method to carry out rock failure test [16–19]. Significant progress has also been made in engineering practice [20–25].

The main methods of measuring plastic zone in engineering field include acoustic wave method, multipoint displacement meter method, geological radar method, seismic wave method, resistivity method, permeability method, borehole camera method, and radioactive element method. The acoustic method is to use the ultrasonic detector to infer the range of the plastic zone by measuring and analyzing the parameters according to the different characteristics of the ultrasonic propagation speed in the rock with different integrity [26]. The multipoint displacement meter method is to measure the displacement of surrounding rock measuring points by displacement measurement and obtain the thickness range of plastic zone through the change of displacement [27]. The ground penetrating radar (GPR) method uses the change of radar reflection wave in different media to detect the location of surrounding rock cracks and obtain the boundary of surrounding rock loose circle [28]. Seismic wave method is used to determine the range of plastic zone according to the change of wave velocity at different rock interface. Permeability method makes use of the permeability of liquid to cracks and infiltrates the liquid into the pores. When there are more cracks in the rock mass, the permeability becomes larger. Finding out the large range of permeability can determine the range of plastic zone. Borehole camera method uses borehole detection for real-time image monitoring and acquisition to observe the fracture development in the rock mass, so as to determine the size of the plastic zone. The radioactive element method uses the characteristics of radioactive elements contained in rocks and absorbed radioactive elements to test the surrounding rock loose zone [22].

In this paper, uniaxial and Brazilian splitting tests are used to analyze the influence of different dip angles of surrounding rock joints on rock strength at laboratory scale. At the same time, the influence of dip angles is analyzed by discrete element numerical simulation. Using the method of acoustic testing, the distribution characteristics of plastic zone of tunnel surrounding rock under different dip angles are analyzed in engineering practice.

2. Engineering Geological Characteristics

Haibaluow tunnel is located on the line from Shangri La to Lijiang in Yunnan Province. Its length is 2262 m, and the maximum buried depth is 461 m. The maximum relative height difference of tunnel crossing is 540 m. The elevation of the tunnel located is 2455–2902 m. According to the internationally accepted altitude classification standard, it belongs to high altitude area, which is a typical carbonaceous slate tunnel. The vertical section is shown in Figure 1.

The tunnel is located in high altitude area with thin air, low air pressure, and poor natural conditions. The geological structure of the tunnel area is complex, and the greatest influence geological structure is Qinghai Tibet Plateau, with many active faults. Zhongdian fault and longpapaqiaohou fault also have a great influence. The tunnel mainly passes through strongly and moderately weathered carbonaceous slate. The structure is mainly thin-layer and cataclastic. The joints and fissures are relatively developed with poor integrality. The local groundwater is relatively developed, and the surrounding rock is easy to soften when encountering water.

Typical carbonaceous slate samples are selected for X-ray fluorescence spectrum analysis. The main minerals in carbonaceous slate are quartz and clay minerals, and the clay minerals are mainly illite and chlorite, as shown in Table 1. The surrounding rock is soft and prone to softening and argillization when meeting with water. Affected by the geological structure, the joint angle of the surrounding rock changes greatly.

3. Influence of Different Joint Dip Angles on Rock Mass Strength

In order to comprehensively analyze the influence of joint angle of surrounding rock on rock strength, the compressive strength and splitting strength under different inclination angles are analyzed. Figure 2 is the comparison diagram of uniaxial compressive strength of rock mass under different
From the diagram, with the increase of joint dip angle, the uniaxial compressive strength of rock presents the pattern of first decreasing and then increasing. It is considered that the strength of rock joints is weak when the rock joints are in the range of 40° to 60°. As a special slate, carbonaceous slate has a low sample rate due to the development of fractures and joints, so there are a few studies on its tensile properties in the current literature. Therefore, it is necessary to carry out in-depth experimental research on Brazilian splitting of carbonaceous slate.

The sample preparation of Brazilian splitting test is divided into two steps: (1) select a 50 mm diameter sleeve to core and cut the disc according to the predetermined inclination angle; (2) smooth the sample with a grinder. The plane along the thickness direction shall be flat to 0.01 mm, and the concave deviation shall not be greater than 0.5°, so that the processed samples can meet the requirements of relevant specifications of rock mechanics test. The experimental results are shown in Figure 3.

Through the calculation and processing of the test data, the average tensile strength is 1.49 MPa, 1.21 MPa, 1.09 MPa, 0.88 MPa, and 0.56 MPa, respectively, at 0°, 30°, 45°, 60°, and 90° inclination. The test results show that the maximum tensile strength of carbonaceous slate is when the joint dip angle is horizontal. The horizontal angle of joint angle represents that the joint inclination angle is 0°, and the strength decreases with the increase of the angle between the joint and the horizontal plane. The variance coefficient $R^2 = 0.88$ indicates that the data is still discrete.

4. Numerical Calculation of Deformation Characteristics of Surrounding Rock under Different Joint Dip Angles

4.1. Model Establishment and Parameter Selection. For the numerical simulation of jointed surrounding rock, there are two kinds of analysis modes: finite element and discrete element. From the simulation principle, the 3D discrete element software is more suitable for practical engineering. The purpose of this study is finding out the relative magnitude of the influence of joint on tunnel stability under different dip angles. So, it is feasible to use 3DEC discrete element software to simulate the joint plane. In order to study the stability and plastic zone distribution characteristics of tunnels with different dip angles, five models were established in this study, which were 0° dip angle, 30° dip angle, 45° dip angle, 60° dip angle, and 90° dip angle.
The joint dip angle is 0 degrees
The joint dip angle is 30 degrees
The joint dip angle is 45 degrees
The joint dip angle is 60 degrees
The joint dip angle is 90 degrees

Figure 2: Influence of rock joint dip angle on uniaxial strength. (a) Uniaxial strength curve of different dip angles. (b) Rock strength under different dip angles.

y = 0.517 + 1.063/(1 + exp ((x – 40.58)/14.8))

Figure 3: Influence of rock joint dip angle on tensile strength. (a) Strength curve of different dip angles. (b) Tensile strength under different dip angles.
In the process of establishing the numerical model, the plane model is used to simulate, and the size of the analysis area has a great influence on the study of tunnel surrounding rock. The model size is 50 m × 50 m, which is five times the tunnel diameter. In the numerical simulation, Mohr-Coulomb criterion and Coulomb slip model are adopted for rock mass discontinuities. The beam element is used to simulate the initial support, and the thickness of the initial support is 350 mm. Referring to the GSI rock classification standard, combined with the numerical inversion analysis in the simulation process, the parameter values of the strength model of carbonaceous slate rock are shown in Table 2, and the model is shown in Figure 4. The horizontal stress is 15 MPa, and the vertical stress is 14 MPa.

4.2. Analysis of Numerical Simulation Results. The displacement of surrounding rock under different dip angles is shown in Figure 5. It is obvious that the joint angle has a great influence on the displacement of tunnel surrounding rock. It can be seen from the figure that, for 45° joint condition, the maximum displacement of the right spandrel of the tunnel is 0.45 m; for 0° joint condition, the maximum displacement of the junction between the free face and joint of the upper tunnel is 0.1 m; for 30° joint condition, the maximum deformation is still in the right spandrel, and the maximum displacement of the junction between the free face and joint is 0.21 m; for 60° joint condition, the maximum deformation is located at the vault, and the deformation is caused by sliding; for 90° joint condition, the maximum displacement of tunnel top is 0.22 m. When the joint angle of the surrounding rock is between 0° and 45°, the deformation of surrounding rock is mainly caused by the bending of thin plate under the action of stress. When the joint angle of surrounding rock is 60°–90°, the deformation is mainly caused by the sliding of surrounding rock along joints.

The variation of surrounding rock displacement under different dip angles is shown in Figure 5(f). It is obvious from the figure that the maximum displacement is 0.45 m under the condition of 45° joint angle. The reason for the maximum displacement at 45° joint angle is that the resultant force of horizontal stress and vertical stress is basically perpendicular to the thin plate.

5. Field Test of Surrounding Rock Plastic Zone and Support Optimization

Acoustic testing method is to judge the integrity of rock mass according to the internal relationship between the physical and mechanical indexes (strength, density, dynamic elastic modulus, etc.) of geotechnical medium and propagation speed of ultrasonic wave in geotechnical medium. If the force (stress) of rock mass is large, the density is large, the integrity of rock mass is good, and the acoustic wave velocity will be correspondingly large.

On the contrary, when the rock mass density is small, the structural plane is developed, the lithology is poor, the groundwater exists, and the acoustic wave velocity will decrease. Therefore, in the same nature of the surrounding rock, the higher the acoustic wave velocity, the better the integrity of the rock mass; the lower the wave velocity, the more broken the rock mass, the higher the existence of cracks, and even the more likely failure. Through testing the longitudinal wave velocity of rock mass at different depths of surrounding rock, according to the change of rock mass wave velocity, the thickness of loose zone of tunnel surrounding rock can be obtained. Figure 6 is the schematic diagram of acoustic double-hole test method.

According to the wave theory in elastic-plastic medium, the wave velocity of stress wave is as follows [29]:

\[ v_p = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \]  

where \( E \) is the elastic modulus of medium (GPa), \( \rho \) is the density of medium (kg/m\(^3\)), \( \mu \) is the Poisson’s ratio of medium, \( L_v \) is the integrity coefficient of loose zone, \( v_p \) is the P wave velocity of rock mass in loose zone (km/s), and \( v_{p1} \) is the P wave velocity of original rock mass (km/s).

Five sections are selected to test the loose circle of the surrounding rock, and four pilot sites are arranged at the left and right side walls and spandrels of each section. No. 1 and No. 2 measuring points are symmetrically arranged 1.5 m above the upper bench excavation line of the left and right side walls. No. 3 and No. 4 measuring points are symmetrically arranged at the spandrel of the upper and lower steps. The down-the-hole drilling is adopted, the hole depth is 8.0 m, and the hole diameter is 40 mm. The dip angles of the surrounding rocks of the five sections are 0°, 30°, 45°, 60°, and 90° respectively, and the layout of the acoustic measuring holes is shown in Figure 7.

The thickness distribution of surrounding rock loose zone is shown in Figure 8. When the joint angle is 0°, the plastic zone is symmetrical. The height of the top plastic zone is about 3.3 m on the free surface. With the increase of the dip angle of surrounding rock, the shape and depth of the plastic zone have obvious changes. When the joint angle is 30 degrees, the plastic zone presents obvious asymmetry. The maximum position of the plastic zone appears in the upper left part of the tunnel, and the maximum depth is 6.2 m. When the joint angle is 45°, the maximum depth of plastic zone is 7.5 m. When the joint angle is 60°, the maximum depth of plastic zone appears in the upper right part of the tunnel, and the maximum depth is 6.1 m. When the joint angle is 90°, the plastic zone also presents symmetrical distribution, and the maximum depth of the plastic zone on the upper right is about 3.6 m.

After the tunnel excavation in layered rock mass, the depth of plastic zone in the area perpendicular to the joint
angle is larger, and the stability of surrounding rock is poor. In view of the large deformation above the arch waist of the tunnel and the characteristics of the surrounding rock when the joint angle is 45°, the length and ring distance of the bolt are optimized on the basis of the original support scheme. The support arrangement is shown in Figure 9. In the dangerous area, the anchor rod is lengthened to 7.5 m and the spacing is 1 m. In other noncritical positions, the length of anchor rod is 4 m and the circumferential spacing is 1 m.

The measured data show that the optimized bolt length can control the deformation of surrounding rock (Figure 10). It is an economical and reliable support scheme to change the layout angle of the anchor and arrange the anchor perpendicular to the bedding plane, which can better

| Lithology          | Rock mass parameters |   | Structural plane parameters |
|--------------------|----------------------|---|-----------------------------|
|                    | Density (kg/m³)      | K (GPa) | G (GPa) | Cᵇ (MPa) | φᵇ | σᵇ (MPa) | Kⁿ (GPa) | k′ (GPa) | C¹ (MPa) | φ¹ | σ¹ (MPa) |
| Carbonaceous slate | 2423                 | 0.49 | 0.26 | 1.58 | 27 | 0.56 | 28.99 | 11.98 | 3.69 | 28 | 3.32 |
Figure 5: Different dip angles and deformation characteristics of surrounding rock. (a) The dominant joint angle 0 degrees. (b) The dominant joint angle 30 degrees. (c) The dominant joint angle 45 degrees. (d) The dominant joint angle 60 degrees. (e) The dominant joint angle 60 degrees. (f) Relationship between dip angle deformations of different surrounding rocks.
Figure 6: Schematic diagram of acoustic double-hole test method.

Figure 7: Layout of acoustic measuring hole.

Figure 8: Distribution characteristics of plastic zone of surrounding rock.
consider the distribution characteristics of joints and fissures, and the influence of different joint dip angles on the stability of surrounding rock is analyzed. The distribution characteristics of plastic zone in practical engineering are analyzed by using acoustic wave testing instrument.

(1) The maximum tensile strength of carbonaceous slate appears when the joint angle is 0° and decreases with the increase of joint angle. With the increase of joint dip angle, the uniaxial strength of rock first decreases and then increases, and the strength of rock joint is weak in the range of 40° to 60°.

(2) According to the simulation results, the stable displacement of tunnel surrounding rock with different dip angles is analyzed, and the maximum displacement under the condition of 45° dip angle joint is obtained.

(3) The results show that the dip angle of surrounding rock has a great influence on the depth and distribution of plastic zone. When the joint dip angle is 45 degrees, the boundary between the plastic zone and the intact rock is the deepest.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors’ Contributions

All authors approved the manuscript for publication.

Acknowledgments

This research was supported by the National Natural Science Foundation of China Youth Fund Project (41702320).

References

[1] X. Liu, Q. Fang, D. Zhang, and Y. Liu, "Energy-based prediction of volume loss ratio and plastic zone dimension of shallow tunnelling," Computers and Geotechnics, vol. 118, p. 103343, 2020.
[2] Y. Xiang and S. Feng, "Theoretical prediction of the potential plastic zone of shallow tunneling in vicinity of pile foundation in soils," Tunnelling and Underground Space Technology, vol. 38, pp. 115–121, 2013.
[3] A.-Z. Lu, G.-S. Xu, F. Sun, and W.-Q. Sun, "Elasto-plastic analysis of a circular tunnel including the effect of the axial in situ stress," International Journal of Rock Mechanics and Mining Sciences, vol. 47, no. 1, pp. 50–59, 2010.
[4] S. A. Massinas and M. G. Sakellariou, "Closed-form solution for plastic zone formation around a circular tunnel in half-space obeying Mohr-Coulomb criterion," Géotechnique, vol. 59, no. 8, pp. 691–701, 2009.
[5] B. Behnam, S. Fazlollah, and M. Hamid, "Prediction of plastic zone size around circular tunnels in non-hydrostatic stress.
field,” International Journal of Mining Science and Technology, vol. 24, no. 1, pp. 81–85, 2014.
[6] G. Li, Y. Hu, Q.-B. Li, T. Yin, J.-X. Miao, and M. Yao, “Inversion method of in-situ stress and rock damage characteristics in dam site using neural network and numerical simulation—a case study,” IEEE Access, vol. 8, pp. 46701–46712, 2020.
[7] L. Gan, M. Weibin, T. Siming, and Z. Wenhao, “Effects of high-prettension support system on soft rock large deformation of perpendicularly crossing tunnels,” Advances in Civil Engineering, vol. 2020, Article ID 6669120, 18 pages, 2021.
[8] G. Li, W. Ma, S. Tian, Z. Hongbo, F. Huabin, and W. Zou, “Groundwater inrush control and parameters optimization of curtain grouting reinforcement for the Jinghai tunnel,” Geofluids, vol. 2021, Article ID 6634513, 10 pages, 2021.
[9] J. Annan, L. Peng, and S. Hongtao, “Shallow depth of the tunnel excavation response research based on CRD method,” Procedia Engineering, vol. 15, pp. 4852–4856, 2011.
[10] H. Y. Shi, Z. K. Ma, Q. J. Zhu, J. J. Shi, and Z. Q. Zhao, “Comparison of shape characteristics of plastic zone around circular tunnel under different strength criteria,” Journal of Mechanics, vol. 36, no. 6, pp. 849–856, 2020.
[11] K. Wu, Z. Shao, S. Qin, W. Wei, and Z. Chu, “A critical review on the performance of yielding supports in squeezing tunnels,” Tunnelling and Underground Space Technology, vol. 114, no. 1, p. 2021, 2021.
[12] K. Wu, Z. Shao, and S. Qin, “An analytical design method for ductile support structures in squeezing tunnels,” Archives of Civil and Mechanical Engineering, vol. 20, no. 3, pp. 1–13, 2020.
[13] K. Wu, Z. Shao, M. Sharifzadeh, S. Hong, and S. Qin, “Analytical computation of support characteristic curve for circumferential yielding lining in tunnel design,” Journal of Rock Mechanics and Geotechnical Engineering, vol. 13, no. 1, pp. 1–13, 2021.
[14] B. Hu, M. Sharifzadeh, X. T. Feng, W. B. Guo, and R. Talebi, “Roles of key factors on large anisotropic deformations at deep underground excavations,” International Journal of Mining Science and Technology, vol. 31, no. 4, pp. 1–16, 2021.
[15] Q. X. Meng, W. Y. Xu, H. L. Wang, X. Y. Zhuang, and T. Rabczuk, “Digisim-an open source software package for heterogeneous material modeling based on digital image processing,” Advances in Engineering Software, vol. 148, p. 102836, 2020.
[16] Z. Tao, C. Zhu, M. He, and M. Karakus, “A physical modeling-based study on the control mechanisms of negative Poisson’s ratio anchor cable on the stratified toppling deformation of anti-inclined slopes,” International Journal of Rock Mechanics and Mining Sciences, vol. 138, p. 104632, 2021.
[17] C. Zhu, M. He, M. Karakus, X. Zhang, and Z. Tao, “Numerical simulations of the failure process of anaclinal slope physical model and control mechanism of negative Poisson’s ratio cable,” Bulletin of Engineering Geology and the Environment, vol. 80, no. 6, pp. 3365–3380, 2021.
[18] Y. Wang, W. K. Feng, R. L. Hu, and C. H. Li, “Fracture evolution and energy characteristics during marble failure under triaxial fatigue cyclic and confining pressure unloading (fc-cpu) conditions,” Rock Mechanics and Rock Engineering, vol. 54, pp. 799–818, 2021.
[19] B. Li, R. Bao, Y. Wang, R. Liu, and C. Zhao, “Permeability evolution of two-dimensional fracture networks during shear under constant normal stiffness boundary conditions,” Rock Mechanics and Rock Engineering, vol. 54, no. 3, pp. 1–20, 2021.
[20] Q. Wang, H. Gao, B. Jiang, S. Li, M. He, and Q. Qin, “In-situ test and bolt-grouting design evaluation method of underground engineering based on digital drilling,” International Journal of Rock Mechanics and Mining Sciences, vol. 138, p. 104575, 2021.
[21] Q. Wang, Q. Qin, B. Jiang et al., “Mechanized construction of fabricated arches for large-diameter tunnels,” Automation in Construction, vol. 124, no. 3, p. 103583, 2021.
[22] A. Li, F. Dai, Y. Liu, H. Du, and R. Jiang, “Dynamic stability evaluation of underground cavern sidewalls against flexural toppling considering excavation-induced damage,” Tunneling and Underground Space Technology, vol. 112, p. 103903, 2021.
[23] Z. Wang, L. Gu, Q. Zhang, S. Yue, and G. Zhang, “Creep characteristics and prediction of creep failure of rock discontinuities under shearing conditions,” International Journal of Earth Sciences, vol. 109, pp. 945–958, 2020.
[24] X. Yang, J. Wang, C. Zhu, M. He, and Y. Gao, “Effect of wetting and drying cycles on microstructure of rock based on sem,” Environmental Earth Sciences, vol. 78, no. 6, pp. 1–10, 2019.
[25] L. Ban, C. Zhu, C. Qi, and Z. Tao, “New roughness parameters for 3d roughness of rock joints,” Bulletin of Engineering Geology and the Environment, vol. 78, no. 6, pp. 4505–4517, 2019.
[26] Q. Bu, G. Hu, Y. Ye, C. Liu, C. Li, and J. Wang, “Experimental study on 2-d acoustic characteristics and hydrate distribution in sand,” Geophysical Journal International, vol. 211, no. 2, pp. 990–1004, 2017.
[27] F. U. Jian-Dang, Y. Y. Zhang, and Y. N. Shi, “Method to measure and calculate deep displacement of surrounding rock based on new dual multi point gauge,” Coal Engineering, no. 5, pp. 81–83+86, 2014.
[28] A. P. Ermakov and A. V. Starovoitov, “The use of the ground penetrating radar (gpr) method in engineering-geological studies for the assessment of geological-cryological conditions,” Moscow University Geology Bulletin, vol. 65, no. 6, pp. 422–427, 2010.
[29] R. Liu, F. Jiang, and X. Zhang, “Measurement of dynamic elastic-plastic fracture toughness under stress wave loading,” Binggong Xuebao/Acta Armamentarii, vol. 22, no. 1, pp. 115–119, 2001.