

Research Article

Model Experimental Study on the Seepage and Failure Features of Tunnel under Wetting-Drying Alternation with Increasing Water Pressure

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Wetting-drying alternation caused by seasonal rainfall and water fluctuation has a negative effect on the rock mass. Model experiments were conducted in this paper to investigate the role of wetting-drying alternation on the seepage and failure features of a tunnel. Water-bearing structure was located in the lateral position of tunnel. The stratum thickness between the tunnel and water-bearing structure was ranged from 20 to 100 mm. The results showed that, with an increase in the wetting-drying alternation number, the pore water pressure increases gradually. The critical water pressure also increases gradually with the increasing thickness of water-resisting stratum. With the increase of the stratum thickness, the permeable area is gradually widened and the water storage capacity becomes stronger. The failure mode of water-resisting stratum under geostress and water pressure can be summarized as two types: fracture failure (thickness of 20 mm) and slippage failure (thickness between 40 and 100 mm), respectively.

1. Introduction

With the vigorous development of economics, the focus of major engineering construction has shifted from plains to the mountainous and karst areas with extremely complex topographic and geological conditions. Deep and long tunnel engineering with high risk has been conducted in karst areas. However, a series of special geological hazards like fractured weak zone, rock burst, and water inrush are encountered in the process of construction [1–4]. Karst tunnel water inrush is one of most common and harmful of these geological hazards [5–9]. According to the statistics, water inrush and other geological hazards induced by water inrush account for 77.3% of the total number of major accidents in tunnel project during the first decade of 21st century in China [10, 11].

The stratum thickness between the tunnel and waterbearing structure is especially crucial to the safety of the karst tunnel. Xu et al. [12] investigated the minimum safety thickness of the rock resisting water inrush from filling-type karst caves located in the top, bottom, and lateral positions to the tunnel. Based on the Yuelongmen tunnel of Chengdu to the Lanzhou railway line in China, Jiang et al. [13] carried out a series of large-scale geomechanical model tests to study the effect of waterproof-resistant slab thickness of surrounding rock on water inrush disaster and established a simplified model to simulate the whole disaster process. Yang and Zhang [14] obtained the expression of the minimum thickness for rock plug in a karst tunnel by means of the upper bound theorem in combination with variational principle. In the area with obvious seasonal rainfall characteristics, the water-bearing cave is often connected with outside by an open channel. The water level in the water-bearing cave rises during the rainy season and falls in the dry season. Under the influence of wetting-drying alternation, fine mineral particles and cementing material in the surrounding rock are dissolved in water and flowed out due to water

pressure, leading to the deterioration of rock mass. With the accumulation of the deterioration effect, the risk of water inrush gradually increases [15–18].

Water environment is one of the important factors affecting rock properties because it can soften and disintegrate the rock and soil mass [19–21]. The grain structure, cementation degree, mineral composition, and crack propagation of rock mass will all change after it is exposed to water, which will eventually lead to the deterioration of physical and mechanical properties of rock mass [22-24]. In recent years, lots of scholars have drawn many valuable conclusions about the effect of wetting-drying alternation on the rock mass. For instance, Doostmohammadi et al. [25] studied the influence of cyclic wetting and drying on mudstone, and they found that the increasing wetting and drying cycles can reduce the time required to reach ultimate swelling. Vergara and Triantafyllidis [26] investigated the swelling behavior of volcanic rocks from the Central Andes of Chile under cyclic wetting and drying. Their results indicated that swelling potential is affected by wetting and drying cycles and this phenomenon only occurs during the wetting phase. Ozbek [27] investigated the variations in physical and mechanical properties of ignimbrites under the influence of wetting-drying and freezing-thawing cycles and discovered the effects of chemical composition, color, and cyclic period on the physical and mechanical properties of rock. Wang et al. [28] examined the irreversible phenomena of argillaceous rocks during wetting and drying processes by combining environmental scanning electron microscope (ESEM) imaging and digital image correlation (DIC) techniques. A modified split Hopkinson pressure bar (SHPB) technique was applied by Zhou et al. [29] to study the influence of wetting and drying cycles on dynamic compressive properties of sandstone. The results showed that the generation of microcracks caused by wetting and drying cycles primarily leads to the reduction in dynamic compressive strength. Qin et al. [30] investigated the effects of drying-wetting cycles on the mechanical properties of altered rock and found that uniaxial compressive strength and elastic modulus gradually decrease with the increase of the drying-wetting cycle number. Zhao et al. [31] studied the evolution of micropores of mudstones under periodic wetting-drying conditions by low-field nuclear magnetic resonance (NMR) and established a significant linear relationship between the increment of porosity and wetting-drying cycle number.

The Liupanshan tunnel is located in Ningxia Hui Autonomous Region of China. The main aquifer types of the rock mass around tunnel are pore and fissure waters in Quaternary loose rock and the bedrock fissure water. In addition, the rainfall is unevenly distributed, depending on the seasons. For example, the rainfall is relatively large in summer and autumn, whereas the rainfall is relatively small in spring and winter. Therefore, in order to investigate the characteristics of water inrush and instability modes of the tunnel under the influence of wetting-drying alternation, large-scale geomechanical models were set up based on the engineering geological background of the Liupanshan tunnel. The effects of stratum thickness on the seepage and failure modes of surrounding rock were also analyzed.

2. Model Experimental Method

2.1. Test Materials and Similarity Ratio. The test materials were selected according to the similarity theory. To improve the accuracy of the test, river sand and talcum powder were selected as the aggregate materials, paraffin as cementing material, and hydraulic oil as the auxiliary material. Preparation and molding of similar material depend on the hot melting and the hardening by cooling of paraffin. In the wetting-drying alternation process, talcum powder and hydraulic oil will be precipitated and separated gradually, which can be used to simulate the loss of clay mineral of surrounding rock mass. The similar material specimens were prepared using these materials with a rational mix ratio.

According to the principle of orthogonal test, the test specimens were designed and fabricated, which include $\varphi 50$ \times 100 mm, φ 50 \times 25 mm, and φ 50 \times 50 mm. Based on the test results of uniaxial compressive, Brazilian splitting and shear tests, the density ρ , porosity Φ , uniaxial compressive strength $\sigma_{\rm c}$, elastic modulus $E_{\rm c}$, tensile strength $\sigma_{\rm t}$, cohesion C, and internal friction φ_0 were measured. The test method was based on the specification of "the specification of engineering rock test method standard (GB/T 502666-2013)" [32]. The mix ratio of similar materials was determined from the specific value of river sand, talcum, paraffin, and hydraulic oil, i.e., 23.0:3.5:1.5:1.0. According to the experimental data on rocks and similar materials, the physical and mechanical properties are listed in Table 1. Besides, according to the engineering geological condition, the geometric similarity ratio and volume-weight similarity ratio in this model experiment were determined as 100 and 1.24, respectively [33, 34].

2.2. Experimental System. In order to investigate the formation process of water inrush with different thickness of water-resisting stratum under wetting-drying alternation, a set of visualization test system for karst tunnel water-inrush disaster was independently developed, as shown in Figure 1. The system mainly consists of geostress loading device, water pressure loading device, data acquisition system, and overall framework. The experimental overall framework is made of a seamless welded steel plate with a thickness of 12 mm, and the net size of the framework is $1000 \times 1000 \times 300$ mm. The 5 cm-apart bolt holes around the frame are reserved to connect the reinforcing plate. A transparent high-strength glass panel is equipped between the frame and reinforcing plate to observe the deformation and failure process of surrounding rock. In addition, in order to provide stable water pressure for the water-bearing structure, the water pressure loading device uses a group of nitrogen cylinder with servo control to provide pressure for the water, which has the advantage of gas-liquid combination. The water-bearing structure is fabricated using the PVC pipe with an inner diameter of 50 mm and thickness of 1.5 mm combined with a stripper rubber.

2.3. Experiment Condition and Production Procedure. Figure 2 shows the sensor arrangement around the tunnel. The height and width of the tunnel are 72 mm and 110 mm, respectively. The stratum thickness *d* between the waterbearing structure and tunnel was ranged from 20 to 100 mm.

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TABLE 1: Physical-mechanical properties of prototype and similar material.

	ρ	Φ	$\sigma_{\rm c}$	σ_{t}	E _c	С	$arphi_0$
Sandstone	2.51 g/cm^3	8.27%	81.83 MPa	11.74 MPa	8.89 GPa	18.61 MPa	43.08°
Similar material	$2.02 {\rm g/cm^3}$	8.73%	323.73 kPa	43.50 kPa	25.78 MPa	79.40 kPa	37.34°



FIGURE 1: Experimental system.

An osmotic pressure gauge, with the measuring range of 1 MPa, was arranged at d/2 away from the right boundary of the water-bearing structure and was connected to data acquisition system via a fixed signal amplifier. The direction of the osmotic pressure gauge is the same with the seepage direction. Three pressure cells were distributed around the tunnel as shown in Figure 2. These pressure cells could measure 1 MPa maximally, with the diameter and thickness of 17 and 8 mm, respectively. The pressure cells were arranged horizon-tally to collect the vertical stress of surrounding rock mass.

The components of similar material were weighted separately in proportion before stirring. In order to achieve the uniform stirring, the talcum powder and river sand were firstly mixed evenly in the blender and the bottom of blender was heated continuously meanwhile. Then, hydraulic oil and melted paraffin were added in the blender, which were stirred well with previous mixed materials.

The lubricating oil was brushed on the frame and interior of the reinforcing plate to reduce the friction. Then, the well-stirred similar materials were poured into test-bed in batches. The similar materials need to be vibrated and tamped one time every 10 cm thick. In addition, waterbearing structure, pressure box, osmotic pressure gauge, and other sensors were buried, respectively, on a preset schedule, once similar materials were laid to the specified position. After pouring similar materials, the model was kept for 48 hours to cool solidified. The geostress loading device was installed on the upper part of the model with a specified in situ stress load applied. The tunnel excavation was carried out after 6 hours' constant in situ stress. Then, the displacement sensor was installed to measure the top-bottom and two walls approaches of tunnel.

The water pressure applied to the model was calculated through a similarity calculation based on the field test data. As shown in Figure 3, when the wetting-drying alternation number N = 1, the water pressure was increased from 0 to 0.03 MPa firstly. The water pressure loading and drying times are about 30 and 120 minutes, respectively. In this drying process, the water in the storage structure will continue to flow out from the surrounding rock of the tunnel, which is actually a process of unloading water pressure. Therefore, the water pressure at the next alternation returns to zero, so as to simulate the wetting-drying alternation process of tunnel surrounding rock. When N = 2, the water pressure



FIGURE 2: Sensor arrangement.



FIGURE 3: Schematic diagram of wetting-drying alternation.

was increased from 0 to 0.06 MPa, and the rest of the process was the same. The increments in each loading cycle are also 0.03 MPa until the formation of water inrush.

3. Results Analysis

3.1. Stable Pore Water Pressure. Figure 4 demonstrates the variation of the pore water pressure in the surrounding rocks in a complete water pressure loading and unloading process when the stratum thickness is 80 mm and the wetting-drying alternation number is 11. The whole process of the variation of pore water pressure can be divided into four stages: rising stage, unstable stage, stable stage, and declining stage. In the rising stage, the pore water pressure increases dramatically, which indicates that the surrounding rock of the tunnel is sensitive to the increment of the groundwater level. When the pore water pressure increases to about

40 kPa, the surrounding rock of the tunnel begins to seep water, but the pore water pressure is still unstable and fluctuates around 40 kPa. After a period of adjustment, the pore water pressure gets to the stable stage. The stable and continuous seepage occurs on the surface of tunnel surrounding rock. Finally, the water pressure in the cave decreases to zero at the end of this wetting-drying alternation; the pore water pressure gradually decreases from the previous stable value. The same evolution curve of the pore water pressure also exhibits in other wetting-drying alternation.

In the rising and unstable seepage stages, the tested pore water pressure of the surrounding rock mass is affected by the water flowing to a certain extent. Therefore, in this study, the average value of pore water pressure in the stable stage was calculated to investigate the influence of wetting-drying alternation on the seepage feature of surrounding rock. Figure 5 displays the variation characteristics of the stable pore water



FIGURE 4: Actual curve of pore water pressure in a water pressure loading process (d = 80 mm, N = 11).



FIGURE 5: Variation in stable water pressure with the increase of wetting-drying alternation number.

pressure in the surrounding rock of the tunnel with different stratum thicknesses and different wetting-drying alternation numbers. When the stratum thickness is fixed, the stable pore water pressure presents a gradual increasing trend with the increment of the wetting-drying number, and the increasing process can be divided into two stages: slow increase and rapid increase. For instance, when the stratum thickness is 80 mm, the stable pore water pressure increases from 0.4 to 3.8 kPa within the first 9 wetting-drying alternations but quickly increases to 121.5 kPa in the following 4 wetting-drying alternations. The variation trend of the pore water pressure in the rock mass is different with different stratum thicknesses. The pore water pressure responds quickly and obviously to the change of the wetting-drying alternation number when the stratum thickness is thin (d = 20,

40 mm). A sharp increase of the pore water pressure only occurs after the wetting-drying alternation number reaches a certain value when the stratum thickness is over 40 mm. In addition, the pore water pressure decreases with the increment of the stratum thickness under the same wetting-drying alternation, which may due to the hysteresis of sensor caused by the large stratum thickness. This phenomenon further indicates that, for porous media, the pore water pressure tends to decline with the increase of seepage path.

Figure 6 shows the seepage and failure process of the tunnel when the stratum thickness is 40 mm. For $N \le 4$, the fluid has not penetrated through the entire thickness of strata and there is no fluid overflow on the tunnel surface. For N = 5, the left side wall of the tunnel starts to seep the water. Then, the area where seepage occurs gradually expands with the



FIGURE 6: Seepage and failure process of tunnel (d = 40 mm).



FIGURE 7: Variations in tunnel deformations with the increase of wetting-drying alternation number: (a) convergence between roof and floor and (b) convergence between two side walls.

increase of the wetting-drying alternation number and the current becomes more and more apparent. For N = 9, the seepage extends to the entire left wall and a macroscopic crack is observed. For N = 10, preserved crack grows and neonatal crack generates at the beginning of the loading process, and the surrounding rock mass continues to separate until the peeling surface is pushed out and caved into the tunnel under the influence of the water pressure. At last, the confined water gushes out quickly from the rock barrier, and the phenomenon of water inrush is formed.

3.2. Displacement and Stress of Surrounding Rock. In order to investigate the evolution characteristics of the surface displacement of the tunnel surrounding rock during the whole process, the displacement meters were embedded in the test model body. The tunnel deformations can be characterized by the relative displacement of the left and right side

walls and the top and bottom surfaces of the tunnel. Figure 7 shows the variations of tunnel deformations in the stable stage with the increase of wetting-drying alternation number. For the surrounding rocks with different stratum thicknesses, the roof and floor are close to each other with the increase of the wetting-drying alternation number so are the left and right side walls. On the whole, under the influence of wetting-drying alternation, the surrounding rock of the tunnel is deformed and the whole tunnel section is in a state of convergence. The horizontal and vertical convergences of the tunnel change slightly and fluctuate in a small range before the complete water inrush but increase sharply in the late stage of water inrush. The peak values of the horizontal and vertical convergences of the tunnel occur at the critical moment of water inrush. The greater the stratum thickness is, the better the integrity of surrounding rock and the smaller the horizontal convergence of two side walls is. It



FIGURE 8: Variations in vertical stresses of surrounding rock with the increase of wetting-drying alternation number: (a) right side wall, (b) roof, and (c) floor, respectively.

is found that the change of horizontal convergence is more significant than vertical convergence in terms of the response speed and response scale. In the model test, the cave was arranged at different positions on the left side of the tunnel, the water pressure in the cave acts directly on the left surrounding rock, which leads to the first deformation of the left surrounding rock. The vertical convergence between the roof and floor before water inrush primarily comes from the vertical displacement of the roof and the heave deformation of the floor. In addition, the roof loses the support of the lower rock mass on account of tunnel excavation; the vertical displacement of the roof would occur due to the dead weight and the pressure of the upper rock mass. Figure 8 shows the changes of vertical stresses of the surrounding rock with the increase of the wetting-drying alternation number. It is found that vertical stresses of the right side wall; the roof and floor get different levels of increment with the increase of the wetting-drying alternation number. The increasing trend of vertical stresses of the right side wall and roof is obvious. They both rise slowly at first and then increase rapidly after reaching a critical value. However, the increase of vertical stress of the floor is hysteretic and the increasing extent is smaller in general than that of the roof. For d = 20 - 100 mm, the increasing extents of the vertical stress of the right side wall are 29.51%, 41.24%, 44.27%, 47.21%, and 53.24%, respectively. The vertical stress of the



FIGURE 9: Water inrush and failure mode of tunnels.

roof increases by 67.13%, 85.67%, 135.60%, 158.04%, and 158.43%, respectively. The greater stratum thickness and more wetting-drying alternations result in the corresponding increment of the permeable area, seepage velocity, and seepage discharge, which further leads to the strength deterioration of the surrounding rock and the increase of porosity. In addition, the roof and side wall of the tunnel are in an unstable state because of the tunnel excavation. This can help explain why the vertical stresses of the roof and right side wall rise with the wetting-drying alternation number. Tunnel excavation makes the roof of the tunnel lose the supporting function of the lower rock mass, and under the influence of the dead weight, it is the most unstable compared with other rock mass. There are differences in the sensitivity and response of the right side wall and roof to the seepage and the strength degradation of the surrounding caused by wetting-drying alternation. The vertical stress of the floor is relatively the least sensitive to the wetting-drying alternation number and stratum thickness, and it always fluctuates around a small value. So, tunnel excavation and wetting-drying alternation have no significant effect on the vertical stress of the floor.

3.3. Failure Feature of Tunnel. Figure 9 exhibits the water inrush and failure mode of tunnels with different stratum thicknesses. It is found that the larger the stratum thickness is, the less obvious the water gushing process is before occurrence of water inrush. When d = 20 mm, the water gushing from the surrounding rock appears to have a "spraying" shape. In general, under the same wetting-drying alternation number, the thicker the water-resisting stratum is, the safer the surrounding rock is. While with the increase of the stratum thickness, the water gushing from the surrounding rock appears in a "linear" shape accompanied by the failure of the surrounding rock mass. The mineral composition and fine

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FIGURE 10: Variations in critical wetting-drying alternation number and critical water pressure with different stratum thicknesses.

clay particles of the water-resisting stratum will be separated out with the influence of wetting-drying alternation, leading to the continuous increase in porosity and reduction in water storage capacity. The majority of water before water inrush is stored in the water-resisting stratum, and the water pressure gradually declines with the flow of water. Therefore, the water gushing process of the tunnel with thick water-resisting stratum is not obvious and the water discharge is small.

The ultimate failure patterns of the tunnel with different stratum thicknesses are significantly different during the instability of the tunnel under the influence of wettingdrying alternation. For d = 20 mm, the surrounding rock is broken by water from the middle part of the left side wall. For d = 40 - 100 mm, the left side wall overall slides to the right and the failure of rock mass occurs at the roof and floor of the left side wall. With the increase of stratum thickness, more wetting-drying alternations are conducted, and the strength of surrounding rock gets continuous degradation. Therefore, the whole surrounding rock is at an unstable state and finally broken by the water pressure accompanied with serious mud inrush.

For the water-resisting stratum with different thicknesses, the final permeable areas show different characteristics after the water inrush of surrounding rock. After comparing the permeable areas showed in Figure 9, it is found that the permeable area is gradually widened with the increase of the stratum thickness. For d = 100 mm, the permeable area extends about 140 mm upwards and 300 mm downwards from the center of the water-bearing structure. The permeable area can intuitively reflect the water storage capacity of the stratum. The thicker water-resisting stratum suffers more wetting-drying alternations, and the pore water pressure gets a continuous increase, which can help explain why the water gushing process before water inrush of thick stratum is not apparent. In addition, according to the principle of minimum energy, water always chooses to flow along the path with the largest slope. So, the water flow path of the cave must be in the direction of the tunnel excavation face.

The completed wetting-drying alternation number and the real-time water pressure in the water-bearing structure when tunnel water inrush happens are, respectively, defined as the critical wetting-drying alternation number and critical water pressure. Figure 10 displays the changes of the critical wetting-drying alternation number and the critical water pressure with different stratum thicknesses. It is found that both the critical wetting-drying alternation number and critical water pressure are positively correlated with stratum thickness as a whole. For d = 20 mm, the water inrush occurs after 6 wetting-drying alternations and the critical water pressure is 0.18 MPa. For d = 100 mm, the water inrush occurs after 15 wetting-drying alternations and the critical water pressure is 0.45 MPa.

Generally, the failure modes of stratum with different thicknesses ranged from 20 to 100 mm under wettingdrying alternation with the increasing water pressure can be divided into two types (fracture failure and slippage failure) in this study, as shown in Figure 11. As stratum thickness is 20 mm, the instability feature presents the fracture failure. The stratum is broken off under geostress and water pressure. When stratum thickness is between 40 and 100 mm, the stratum ends are damaged and fractured, and the stratum structure shows overall slippage.

4. Conclusions

In this study, based on the engineering background of the Liupanshan tunnel (China), physical model tests were set up to explore the seepage and failure features of the karst tunnel with different thicknesses of the water-resisting stratum under the wetting-drying alternation. Some of the conclusions drawn are as follows:

 Both the critical wetting-drying alternation number and critical water pressure increase gradually with the increasing thickness of water-resisting stratum. Besides, with the increase of the alternation number,



FIGURE 11: Failure modes of stratum.

the pore water pressure of the surrounding rock mass increases gradually, which shows a trend of small fluctuation at first and then rapid increase

- (2) The smaller the thickness of water-resisting stratum is, the more obvious the change of pore water pressure will be. In addition, with the increase in the thickness of water-resisting stratum, the permeable area is gradually widened. The water storage capacity also becomes stronger
- (3) The vertical stresses of the right side wall, roof, and floor get different levels of increment with the increase of the wetting-drying alternation number. The stress variation of the roof surrounding rock is the most significant, followed by the right wall, and the floor-surrounding rock is the smallest. And the horizontal and vertical convergences of tunnel change slightly and fluctuate in a small range before the complete water inrush but increase sharply in the late stage of water inrush

In the actual tunnel projects, the location and scale of karst cave are also crucial to the stability of the tunnel. In addition, more model tests will be conducted to study the whole deformation field evolution process of the surrounding rock mass around the tunnel by the digital image correlation method.

Data Availability

The original data used to support the findings of this study are available from the corresponding author (hjsu@cumt.edu.cn) upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References

- L. Li, W. Tu, S. Shi, J. Chen, and Y. Zhang, "Mechanism of water inrush in tunnel construction in karst area," *Geomatics*, *Natural Hazards and Risk*, vol. 7, no. sup1, pp. 35–46, 2016.
- [2] D. Liang, Z. Jiang, S. Zhu, Q. Sun, and Z. Qian, "Experimental research on water inrush in tunnel construction," *Natural Hazards*, vol. 81, no. 1, pp. 467–480, 2016.
- [3] T. T. Zhu and D. Huang, "Experimental investigation of the shear mechanical behavior of sandstone under unloading normal stress," *International Journal of Rock Mechanics and Mining Sciences*, vol. 114, pp. 186–194, 2019.
- [4] Y. Bai, R. Shan, Y. Ju, Y. Wu, P. Sun, and Z. Wang, "Study on the mechanical properties and damage constitutive model of frozen weakly cemented red sandstone," *Cold Regions Science and Technology*, vol. 171, article 102980, 2020.
- [5] S. Li, Z. Zhou, L. Li, Z. Xu, Q. Zhang, and S. Shi, "Risk assessment of water inrush in karst tunnels based on attribute synthetic evaluation system," *Tunnelling and Underground Space Technology*, vol. 38, pp. 50–58, 2013.
- [6] Q. Zhu, Q. Miao, and S. Jiang, "On karst water inrush (gushing) geological environment in Pingyang tunnel," *Applied Mechanics and Materials*, vol. 580-583, pp. 1008–1012, 2014.
- [7] S. Wang, L. P. Li, S. Cheng, H. J. Hu, M. G. Zhang, and T. Wen, "Risk assessment of water inrush in tunnels based on attribute interval recognition theory," *Journal of Central South University*, vol. 27, no. 2, pp. 517–530, 2020.
- [8] X. Li and Y. Li, "Research on risk assessment system for water inrush in the karst tunnel construction based on GIS: case study on the diversion tunnel groups of the Jinping II Hydropower Station," *Tunnelling and Underground Space Technol*ogy, vol. 40, pp. 182–191, 2014.
- [9] D. D. Pan, S. C. Li, Z. H. Xu, P. Lin, and X. Huang, "Experimental and numerical study of the water inrush mechanisms of underground tunnels due to the proximity of a water-filled karst cavern," *Bulletin of Engineering Geology and the Environment*, vol. 78, no. 8, pp. 6207–6219, 2019.
- [10] J. Q. Guo, Y. Qian, J. X. Chen, and F. Chen, "The minimum safe thickness and catastrophe process for water inrush of a karst tunnel face with multi fractures," *Processes*, vol. 7, no. 10, p. 686, 2019.
- [11] B. Zhang and Z. Lin, "A computing method for sand inrush quantity through a borehole in Longde coal mine," *Advances in Civil Engineering*, vol. 2018, Article ID 4842939, 11 pages, 2018.
- [12] Z. H. Xu, J. Wu, S. C. Li, B. Zhang, and X. Huang, "Semianalytical solution to determine minimum safety thickness of rock resisting water inrush from filling-type karst caves," *International Journal of Geomechanics*, vol. 18, no. 2, article 04017152, 2018.
- [13] H. M. Jiang, L. Li, X. L. Rong, M. Y. Wang, Y. P. Xia, and Z. C. Zhang, "Model test to investigate waterproof-resistant slab minimum safety thickness for water inrush geohazards," *Tunnelling and Underground Space Technology*, vol. 62, pp. 35–42, 2017.
- [14] Z. H. Yang and J. H. Zhang, "Minimum safe thickness of rock plug in karst tunnel according to upper bound theorem," *Journal of Central South University*, vol. 23, no. 9, pp. 2346–2353, 2016.
- [15] F. Zhao, Q. Sun, and W. Zhang, "Combined effects of salts and wetting-drying cycles on granite weathering," in *Bulletin of Engineering Geology and the Environment*, 2020.

- [16] W. Liu and Z. H. Zhang, "Experimental characterization and quantitative evaluation of slaking for strongly weathered mudstone under cyclic wetting-drying condition," *Arabian Journal* of *Geosciences*, vol. 13, no. 2, 2020.
- [17] Y. J. Qi, T. Li, R. H. Zhang, and Y. Chen, "Interannual relationship between intensity of rainfall intraseasonal oscillation and summer-mean rainfall over Yangtze River basin in eastern China," *Climate Dynamics*, vol. 53, no. 5-6, pp. 3089–3108, 2019.
- [18] S. Phakula, W. A. Landman, and A. F. Beraki, "Forecasting seasonal rainfall characteristics and onset months over South Africa," *International Journal of Climatology*, vol. 38, pp. E889–E900, 2018.
- [19] E. Kim and H. Changani, "Effect of water saturation and loading rate on the mechanical properties of red and buff sandstones," *International Journal of Rock Mechanics and Mining Sciences*, vol. 88, pp. 23–28, 2016.
- [20] Q. Yin, G. Ma, H. Jing et al., "Hydraulic properties of 3d rough-walled fractures during shearing: an experimental study," *Journal of Hydrology*, vol. 555, pp. 169–184, 2017.
- [21] Y. Ju, Q. G. Zhang, Y. M. Yang, H. P. Xie, F. Gao, and H. J. Wang, "An experimental investigation on the mechanism of fluid flow through single rough fracture of rock," *Science China–Technological Sciences*, vol. 56, no. 8, pp. 2070–2080, 2013.
- [22] P. Sumner and M. J. Loubser, "Experimental sandstone weathering using different wetting and drying moisture amplitudes," *Earth Surface Processes and Landforms*, vol. 33, no. 6, pp. 985– 990, 2008.
- [23] Z. Zhou, X. Cai, D. Ma, L. Chen, S. Wang, and L. Tan, "Dynamic tensile properties of sandstone subjected to wetting and drying cycles," *Construction and Building Materials*, vol. 182, pp. 215–232, 2018.
- [24] Q. Sun and Y. L. Zhang, "Combined effects of salt, cyclic wetting and drying cycles on the physical and mechanical properties of sandstone," *Engineering Geology*, vol. 248, pp. 70–79, 2019.
- [25] R. Doostmohammadi, M. Moosavi, T. Mutschler, and C. Osan, "Influence of cyclic wetting and drying on swelling behavior of mudstone in south west of Iran," *Environmental Geology*, vol. 58, no. 5, pp. 999–1009, 2008.
- [26] M. Vergara and T. Triantafyllidis, "Swelling behavior of volcanic rocks under cyclic wetting and drying," *International Journal of Rock Mechanics and Mining Sciences*, vol. 80, pp. 231–240, 2015.
- [27] A. Ozbek, "Investigation of the effects of wetting-drying and freezing-thawing cycles on some physical and mechanical properties of selected ignimbrites," *Bulletin of Engineering Geology and the Environment*, vol. 73, no. 2, pp. 595–609, 2014.
- [28] L. Wang, M. Bornert, E. Heripre, D. Yang, and S. Chanchole, "Irreversible deformation and damage in argillaceous rocks induced by wetting/drying," *Journal of Applied Geophysics*, vol. 107, pp. 108–118, 2014.
- [29] Z. Zhou, X. Cai, L. Chen, W. Cao, Y. Zhao, and C. Xiong, "Influence of cyclic wetting and drying on physical and dynamic compressive properties of sandstone," *Engineering Geology*, vol. 220, pp. 1–12, 2017.
- [30] Z. Qin, X. Chen, and H. Fu, "Damage features of altered rock subjected to drying-wetting cycles," *Advances in Civil Engineering*, vol. 2018, Article ID 5170832, 10 pages, 2018.

- [31] Y. Zhao, S. Ren, D. Jiang, R. Liu, J. Wu, and X. Jiang, "Influence of wetting-drying cycles on the pore structure and mechanical properties of mudstone from Simian Mountain," *Construction and Building Materials*, vol. 191, pp. 923–931, 2018.
- [32] People's Republic of China National Standard, *Engineering rock test method standard (GB/T 50266–2013)*, China Planning Publishing House, Beijing, 2013.
- [33] L. Liu, Z. Li, X. Liu, and Y. Liu, "Frost front research of a coldregion tunnel considering ventilation based on a physical model test," *Tunneling and Underground Space Technology*, vol. 77, pp. 261–279, 2018.
- [34] Q. Tian, J. Zhang, and Y. Zhang, "Similar simulation experiment of expressway tunnel in karst area," *Construction and Building Materials*, vol. 176, pp. 1–13, 2018.