Experimental Study on the Failure Mechanism of Tunnel Surrounding Rock under Different Groundwater Seepage Paths

Yingchao Wang,1, 2 Yang Liu,1 Yongliang Li,1 Wen Jiang,1 and Yueming Wang1

1 State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining & Technology, Xuzhou, Jiangsu 221116, China  
2 School of Mechanics & Civil Engineering, China University of Mining & Technology, Xuzhou, Jiangsu 221116, China

Correspondence should be addressed to Yingchao Wang; wangyingchao@cumt.edu.cn

Received 1 June 2020; Revised 10 February 2021; Accepted 21 March 2021; Published 8 May 2021

Academic Editor: Micòl Mastrocicco

Copyright © 2021 Yingchao Wang 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.

The influence of groundwater on tunnel engineering is very complicated. Due to the complexity of water flow water pressure transfer and uncertain defects in the stratum, all of which are key factors with regard to the design of tunnel engineering. Therefore, the variation of surrounding rock during excavation and the deformation and failure of soft surrounding rock under different seepage paths of underground water after excavation systematically. Experimental results showed that the stress change of surrounding rock caused by tunnel excavation can be divided into 3 stages: stress redistribution, stress adjustment, and stress rebalancing. In the process of water pressure loading, water flow rate is closely related to the experimental phenomenon. The between stable loading water pressure pore water pressure of the tunnel surrounding rock and the distance from the measuring point to the edge of the tunnel obey the exponential function of the decreasing growth gradient. With the increase of loading pressure, the pore water pressure and stress at the top of the tunnel increase, and the coupling of stress field and seepage field on both sides of surrounding rock more and more intense. The failure process of the tunnel can be divided into 6 stages according to the damage degree. The final failure pattern of the surrounding rock of the tunnel is mainly determined by the disturbed area of excavation. The arched failure area and the collapse-through failure area are composed of three regions. The surrounding rock is characterized by a dynamic pressure arch in the process of seepage failure, but it is more prone to collapse failure at low water pressure. The results of this study are the progressive failure mechanism of tunnel under different groundwater seepage paths and would be of great significance to the prevention of long-range disasters.

1. Introduction

With the rapid development of the transportation industry, tunnel engineering is widely used in infrastructure construction and plays an important role in railway engineering, highway engineering, water conservancy engineering, etc. However, the development of tunnel engineering shows the trends of longer, larger, and deeper, the construction environment becomes more and more complex; thus, the disasters such as collapse, water, and mud inrush often occur, which seriously affect the safety of tunnel engineering and restrict the economic development of the country [1–7]. The disaster caused by groundwater seepage is a common problem in tunnel engineering. Due to the complexity of groundwater seepage and hydraulic pressure transmission
failure mechanism of surrounding rock under the condition of groundwater seepage can be studied from three angles: theoretical analysis, model experiment, and numerical simulation. Since 1856, Darcy, a French hydraulic engineer, summarized the most basic seepage law through the seepage experiment of homogeneous sand, namely, Darcy’s law. Subsequently, scholars from all over the world deduced a series of seepage formulas based on Darcy’s law, such as nonlinear binomial seepage law and nonlinear power function seepage law. In recent years, the groundwater seepage of rock mass is often associated with destruction of surrounding rock; many scholars have made plenty of researches on the influence of groundwater seepage on tunnel surrounding rock, put forward a variety of seepage-rock coupling calculation equations, and elaborated the mechanical effect of seepage on fractured rock. For example, Wang et al. established a sharp point mutation model by catastrophe theory to reveal the collapse mechanism of shallow tunnel under rainfall penetration [8]. Wang et al. proposed the coupling analysis equation of seepage and stress in fractured rock mass [9]. The evolution law of mechanical properties of rock mass under the action of seepage was revealed. It is mainly believed that rainfall or groundwater softens surrounding rock and supporting structure, leading to a decrease in shear strength of surrounding rock [10–13]. At the same time, the hydraulic fracturing can also lead to the cracking of tunnel surrounding rock, further reducing the stability of surrounding rock. Yu studied the stability of surrounding rock of underwater tunnel, and the results were applied to the Jiaozhou Bay subsea tunnel in Qingdao successfully [14]. The numerical calculation of groundwater seepage and the study about influence of fissure and aquifer further promoted the study of the coupling effect of stress field and seepage field [15–17].

With the development of computer technology, numerical simulation methods mainly include finite element method (FEM), finite difference method (FDM), boundary element method (BEM), discrete element method (DEM), back Analysis, lagrangian analysis are often used in research. And the rise of discrete fracture network (DFN) technology makes the simulation effect is closer to the practical condition [18–21]. DEM, combined with theoretical calculation or model test, can be used to predict the hydraulic pressure behind the lining, surrounding rock deformation, and support parameters under different conditions during the design stage [22–30], so as to make reasonable support design to reinforce the surrounding rock of the tunnel and avoid the occurrence of disasters [14, 31–33].

In terms of physical model experiment, scholars are not limited to the study of the development process of fracture, creep law, and change of permeability coefficient under groundwater seepage; the influencing factors and failure mechanism of tunnel failure are also considered [34–36]. Wang simulated the tunnel collapse process during the excavation and proposed the progressive failure mechanism of surrounding rock under the influence of groundwater seepage [37]. Li conducted an experimental study on the failure mechanism of slope caused by typhoon and rainstorm, revealing that groundwater can not only affect the characteristics of aquifer soil but also have adverse effects on the upper slope of the impervious layer [38]. Wang made some preliminary exploration on the collapse mechanism of loose surrounding rock of shallow tunnel under rainwater penetration and established the corresponding sharp point mutation theoretical model [39]. Li et al. developed a new fluid-solid coupling model experiment system to reveal the evolution law of surrounding rock stress, displacement field, and seepage field of submarine tunnel during the construction [40]. Wang et al. established a 3D geological model experiment system to study the influence of Solid-fluid interaction between surrounding rock and water body on the stability of subsea tunnel and revealed the response rule of displacement, seepage pressure, stress, strain, and other characteristic parameters to timeliness [41]. Zhou et al. carried out the water inrush experiment of deeply buried long tunnel through 3D visualization fluid-solid coupling experiment system [42]. The whole process including fracture formation, expansion, penetration of water channel, and water inrush in karst strata was reproduced during the excavation and hydraulic loading process vividly. Aiming at the problem that tunnel in karst areas is prone to be damaged under groundwater seepage, Yang et al. adopted the similarity theory to construct a slope model, thus revealed the destruction process and law of water inrush in tunnel due to seepage from filled karst conduct [43].

Combined with the above discussion, it is not difficult to find that the current researches on groundwater seepage in tunnels are mostly based on fluid-solid coupling and the analysis of physical and chemical effects of water on rock mass, so as to provide suggestions for the prevention of engineering disasters. However, there are few studies on the progressive failure mechanism of tunnel under different seepage paths [17, 44]. The study on the characteristics of progressive failure of surrounding rock is still incomplete [45, 46]. Therefore, this work simulates the change of surrounding rock and the failure process of surrounding rock in the process of tunnel excavation under the action of continuous water source by self-designed experimental device to improve the theory of surrounding rock deformation under seepage and provide a reference to the prevention of engineering disasters.

2. Materials and Methods

2.1. Model Box. Laboratory experiments were performed by self-designed test device, which is shown in Figure 1. The length × height × width of the model box is 1.0 m × 1.0 m × 0.3 m. In order to meet the observation requirement during the test, the front of the model box is made of 12 mm thick plexiglass. A water pipe and a valve with diameter of 3/4 inch are installed at 200 mm intervals on the left side of the model box and the drain pipe is arranged at the bottom of the right side. The tunnel mouth is located on the lower middle part of the glass plate with a net width of 137.8 mm and a net height of 100 mm.

2.2. Experimental Material. Before the test, a layer of hydraulic oil is added to the inner layer of the box to prevent water from flowing along the inner wall of the model box.
The packing is made of similar materials with a height of 0.83 m, a geometric similarity ratio of 1 : 50, and a weight-to-weight similarity ratio $C_r = 1$. According to the similarity theory, the similarity ratio of Poisson’s ratio, strain, and internal friction angle is obtained, $C_\nu = C_\varepsilon = C_\phi = 1$; the similarity ratio of strength, stress, cohesion, and elastic modulus is $C_R = C_\sigma = C_c = C_E = 50$.

According to the test design, the similar materials of surrounding rock can self-stabilize during the tunnel excavation and after the completion of the excavation, and maintain a certain strength when it meets water. However, after the tunnel excavation, it will gradually collapse under the action of water. After analyzing the known research results, the mix proportion of the final materials and components was determined, sand : cement : clay : hydraulic oil = 8 : 0.6 : 0.4 : 0.1.

2.3. Data Collection. In this test, GDB3816 static strain gauge is used for data collection. The schematic of measuring points arrangement is shown in Figure 2, in which T1, T3, T5, T7, T9, T11 are the strain earth pressure boxes with the measuring range of 50 kPa, T2, T4, T6, T8, T10, T12 are the strain pore water pressure gauges with the measuring range of 50 kPa. The distance between each measuring point is 0.5B (B is the tunnel height) equal to 50 mm. T13, T14, T15 at the top are the displacement meters with measuring range of 5 cm, which are arranged at the middle line and 20 cm to the left and right of the middle line.

Before the test, the earth pressure box was calibrated with sand marks, the pore water pressure was calibrated by the oil standard method, and the displacement meter and earth pressure box were all supplied with external force through DNS100.

2.4. Test Methods. To investigate the effects of excavation and underground water on the surrounding rock, the test process is divided into two steps. First, the excavation is carried out under the condition that the water content of the surrounding rock is low. Second, after the excavation is completed, a certain amount of water is continuously injected from the pipe on the left side of the model box (the loading water pressure $P_c = 50$ kPa) until the tunnel collapses. Different water supply locations (H) simulate different seepage paths. The specific test scheme is shown in Table 1.

3. Results and Discussion

3.1. Analysis of Tunnel Excavation Process. The tunnel excavation method adopts the full-section method. Stress variation curves around the tunnel during the excavation are shown in Figure 3. It can be observed that the stress variation of the surrounding rock of the tunnel can be divided into three stages, namely, stress redistribution, stress adjustment phase, and stress reequilibration phase.

It can be seen from Figure 3(a) that the radial stress of surrounding rock at the top of the tunnel decreases as a result of excavation, and the closer it is to the tunnel, the greater the change of the stress value would be. Moreover, the stress change at the top of the tunnel is significantly greater than that at the two sides.

It can be seen from Figure 3(b) that the radial stress caused by excavation at two points decreases slightly, but the closer the stress change value of the measuring point is, the more complex the rule becomes. The curve of the near-tunnel measuring point T5 is taken as an example. At the beginning of excavation, the stress increases first and then decreases gradually with the loss of rock mass and the uncertainty of artificial excavation, the stress gradually decreases.

As can be seen from Figure 3(c), the excavation caused the tangential stress of the tunnel. However, at the beginning of the excavation, the point T1 near the tunnel increases in a moment, then fluctuated and decreased. Meanwhile, point T7 was far away from the tunnel, which showed a steady rise and the growth rate was also lower than T1.
As can be seen from Figure 3(d), the settlement values of T13, T14, and T15 are 0.32 mm, 1.47 mm, and 0.32 mm, respectively, which indicate that the surface settlement is the largest above the tunnel and the disturbance has the same effect on both sides of the tunnel.

3.2. Analysis of Failure Process by Adding Water under Different Seepage Paths. After the excavation is completed and the sensor data are stabilized, the water pressure is loaded and the variation characteristics of various factors during the loading and destruction process are analyzed.

3.2.1. Change Characteristics of Inflow and Outflow Rate. Taking the test condition \( H = 13 \) cm as an example, the change curve of inflow and outflow rate during the process of hydraulic loading is shown in Figure 4.

According to the curve forms in Figures 3–4, the whole hydraulic loading process can be divided into three stages.

### Table 1: Test scheme.

| Number          | Water supply location (H)/cm | Surrounding rock grade |
|-----------------|------------------------------|------------------------|
| Test scheme I   | 13                           | Level IV               |
| Test scheme II  | 33                           | Level IV               |
| Test scheme III | 53                           | Level IV               |
| Test scheme IV  | Not loading                  | Level IV               |

In the first 10 min, the inflow rate rises gradually, while the outflow rate is almost zero, which indicates that the surrounding rock is relatively dense at first, and there is no through-flow seepage channel, groundwater only flows along the fractures of the rock mass, and the surrounding rock is in the unsaturated stage.

As the fractures gradually form channels due to water flow, the inflow rate increases, and the surrounding rock gradually becomes saturated. Meanwhile, the outflow rate
Figure 3: Continued.
gradually increases, indicating that the seepage path forms a stable channel, and the surrounding rock enters into the saturated seepage stage.

When the outflow curve reaches a peak at 17 min, the tunnel surrounding rock collapses. Subsequently, the outflow rate gradually decreases, the water inrush occurs, and the inflow curve tends to be stable, which indicates that the seepage channel through the tunnel section has been formed inside the model material to reach the stable stage of water inflow and outflow. Therefore, it can be seen that the change of inflow and outflow rate of the model material is closely related to the experimental phenomenon.

3.2.2. Characteristics of Seepage Law of Surrounding Rock in Different Parts. Taking the test condition \( H = 13 \, \text{cm} \) as an example, under the action of the stable loading water
pressure $P_c$, the difference $\Delta P$ between pore water pressure and $P_c$ at different measuring points within the range of 2 times the tunnel height ($F = 2B$) is calculated, and the relationship between $\Delta P$ and the distance to the tunnel edge is obtained as shown in Figures 5, 6, and 7, where $M$ represents the mass of the loading water flow, $V$ represents the distance to the top of the tunnel, $L$ represents the distance to the left edge of the tunnel, and $T$ represents the distance from the right edge of the tunnel.

As can be seen from Figure 5, the $\Delta P$ value at the top of the tunnel gradually increases at the initial stage of water loading, then decreases slightly with the loss of particles, and then increases again with the occurrence of water and mud inrush until the pore water pressure at the top of the tunnel reaches a stable state in the final collapse state. Therefore, $\Delta P$ at the measuring point $V = 50$ mm shows a process of increasing first, then decreasing and then increasing to a stable state.

It can be seen from Figures 6 and 7 that there is no stable seepage channel inside the model in the initial stage of loading water, and the $\Delta P$ value of the left and right measuring points of the tunnel is small. With the increase of the loading water volume, the migration effect is gradually enhanced, and the smooth seepage channel is formed along the large crack inside the rock mass, which weakens the obstruction effect on the water flow, so that the $\Delta P$ value of the left and right measuring points of the tunnel shows a trend of increasing, but the $\Delta P$ value of the left measuring point is greatly changed. On the right side, the $\Delta P$ value of the right measuring point tends to be stable when the loading water is equal to 8 kg, which is smaller than the left side.

In the range of 2 times tunnel height ($F = 2B$), the non-linear fitting relationship between the $\Delta P$ value of the measuring point under different loading water and the distance from the measuring point to the edge of the tunnel can be expressed as an exponential function with the growth gradient gradually decreasing.

$$\Delta P = m(1 - e^{nt}),$$

where $m$ and $n$ are the fitting parameters, $S$ represents the distance to the edge of the tunnel, and the error coefficient $R^2$ of the test value and the fitted curve under different loading water conditions is in the range of 0.9466-0.999, which indicates that the percolation law around the different loading water tunnel is nonlinear. The fitting is more in line with the above formula. The magnitude of the parameter $m$ determines the stable value of the final curve, that is, the stable value of the seepage water pressure. The value of parameter $n$ affects the gradient of osmotic water pressure.

### 3.3. Analysis of Hydraulic Coupling Characteristics under Different Seepage Paths.

In order to study the influence of different loading water pressure positions on the pore water pressure and stress of the rock mass near the tunnel section, under the condition of $H = 13$ cm, $H = 33$ cm, $H = 53$ cm, the curve of T9 and T10 at the top of the tunnel, the T1 and T2 on the left side of the tunnel, and the T5 and T6 on the right side of the tunnel are shown in Figure 8.

(1) It can be seen from Figures 8(a)–8(c) that the pore water pressure and stress variation of the surrounding rock at the top of the tunnel increases with the increase of $H$. When $t = 600$ s, the change of pore water pressure at the top point T10 of the tunnel precedes the stress change of the surrounding rock measurement point T9. It is presumed that the change of pore water pressure causes the stress change, and the change of stress at $t = 1700$ s causes the fluctuation of
pore water pressure curve showing that there is a mutual influence between the two

(2) It can be seen from Figures 8(d)–8(i) that as $H$ increases, the area enclosed by the pore water pressure curve and stress curve at the left and right points of the tunnel gradually decreases, and the value of the final change is getting more and more close, indicating that the degree of interaction between the two becomes intense with the increase of $H$, and the variation range of the two is closer due to the increase of $H$

(3) It can be seen from Figures 8(a), 8(d), and 8(g) that when the surrounding rock stress changes abruptly, the pore water pressure changes at the measuring points T10, T2, and T6 under $H = 13$ conditions are, respectively, for 19.12 kPa, 15.59 kPa, and 10.78 kPa; the sudden release of pore water pressure accumulation energy marks the formation of seepage channel, so the seepage channel is most easily formed at the top of the tunnel, and the development of the seepage channel on the right side of the tunnel is the worst

3.4. Analysis of Surface Settlement Characteristics under Different Seepage Paths. The settlements of surface measurement points T13, T14, and T15 under different working conditions are summarized in Figure 9.

It can be seen from the Figure 9 that the final settlement of the T13 on the left side of the tunnel is always greater than the settlement of the T15 on the right side, regardless of whether it is under the same seepage path, and the settlement increased with the depth of the water pressure loading. The
settlement shows a nearly uniform linear growth with a gradient of about 10%. When the water pressure loading position is in a shallow soil layer that is closer to the surface, the settlement value of T13 is the largest, but with the depth of the water pressure increase, the settlement value of T14 increases, and gradually becomes the maximum among T13, T14, and T15.

3.5. Analysis of Water Inrush in Weak Rock Tunnel Mud Evolution Process. Through experiments, it is found that the tunnel failure process under different working conditions can be roughly divided into six stages, among which the test process phenomenon under the condition of water pressure loading position \( H = 53 \) is shown in Figure 10.

As can be seen from Figure 10, there is no obvious collapse on the tunnel surface after the excavation is completed. When \( M = 9 \) kg, the water seepage phenomenon begins to appear on the left wall of the tunnel, and the local rock mass of the tunnel has cracks, which indicates that a stable seepage channel has been formed in the model. When \( M = 10 \) kg, the left arch shoulder of the tunnel collapses locally, accompanied by a small amount of mud-water mixture flowing out, which indicates that the surrounding rock of the tunnel no longer has sufficient bearing capacity due to the scouring of groundwater. When \( M = 11 \) kg, obvious cracks begin to appear in the surrounding rock of the upper layer of the tunnel, and the amount of mud-water mixture gushing out gradually increases, which indicates that the seepage passage begins to expand rapidly and gradually penetrate, and the unloading area of the rock mass becomes larger. When \( M = 12 \) kg, the tunnel starts to suffer from arch-shaped collapse that continues to expand leftwards and upwards, which indicates that a rock mass with a certain thickness and capable of bearing water pressure disturbance is formed in the
surrounding rock of the tunnel at a certain moment, and the range of this rock mass changes dynamically with water pressure loading; when \( M = 13 \) kg, the collapse mode changes from arch collapse to downward sliding of the upper left rock mass. The flow rate and velocity of the mud-water mixture increased sharply, and the collapse arch gradually expands into a passage penetrating to the surface.

Under three test conditions, the phenomenon of water and mud inrush appeared, and the tunnel collapse morphology changed from arch collapse to penetration collapse. However, the larger the value of the loading water pressure position \( H \), the more the loading water quantity \( M \) corresponding to various collapse forms. After the test data are stabilized, the final stable failure form of tunnel collapse in three different seepage paths is shown in Figure 11.

It can be seen from Figure 11 that under different seepage conditions, the final failure mode of tunnel surrounding rock can be roughly divided into three areas, namely, excavation disturbance zone, arched failure zone, and collapse failure zone. The excavation disturbance zone is the surrounding rock unloading area caused by excavation, which is determined by the range of cracks around the rock mass after excavation. The arched failure zone is caused by the internal pressure arch effect, determined by the extent of the landslide without the through-fracture. Collapse failure zone is gradually formed by the cracks that penetrate into the surface, which can be directly determined according to the experimental phenomena. The test results under three different seepage paths are summarized. The final failure mode of the tunnel surrounding rock has the following rules:

1. The damage of the surrounding rock of the tunnel starts from the left side of the arch, and the two main cracks formed along the upper part of the tunnel develop upward. The main crack is the widest and deepest crack in the whole tunnel collapse process, where severe water inrush occurs. The surface subsidence and fissure development in this area are also the fastest. When \( H = 13 \) cm, the distance between the two main cracks spread to the surface is 29 cm, and the surface subsidence of the tunnel section axis to the right side of the surface is 26 cm. The

\[
\Delta P = 0.0301 (1 - e^{-0.0281T})
\]

\( R^2 = 0.9591 \)

\[
\Delta P = 10.0822 (1 - e^{-0.0276T})
\]

\( R^2 = 0.9545 \)

\[
\Delta P = 10.09 (1 - e^{-0.0267T})
\]

\( R^2 = 0.9466 \)

\[
\Delta P = 10.09 (1 - e^{-0.0267T})
\]

\( R^2 = 0.9466 \)

Figure 7: Relationship between pore water difference \( \Delta P \) and distance \( T (F = 2B) \).
Figure 8: Continued. 

(a) $H = 13 \text{ cm}, T9 \text{ and T10}$

(b) $H = 33 \text{ cm}, T9 \text{ and T10}$

(c) $H = 53 \text{ cm}, T9 \text{ and T10}$

(d) $H = 13 \text{ cm}, T1 \text{ and T2}$

(e) $H = 33 \text{ cm}, T1 \text{ and T2}$

(f) $H = 53 \text{ cm}, T1 \text{ and T2}$
maximum settlement position is located on one of the main cracks; when $H = 33$ cm, the main crack spacing is 27 cm as shown in the sketch diagram, and the maximum settlement of the surface with no collapsed is located directly above the tunnel. The above phenomena indicate that with the increase of $H$, the spacing of the two main cracks to the ground becomes smaller, while the extent of the surface subsidence on the right side increases.

(2) The maximum horizontal spacing of the arched collapse area under the three working conditions is 12 cm, 13 cm, and 19 cm, respectively, that is, the maximum horizontal spacing of the arched collapse area increases with the increase of the buried water pressure depth $H$, and the development speed of the collapsed arch also slows down with the increase of $H$

The statistics of different damage areas under different seepage paths are shown in Figure 12.

It can be seen from Figure 12 that under different seepage conditions, the excavation disturbance zone in the final failure mode of the tunnel model accounts for 11.98%, 11.44%,

\[ \text{Figure 8: Variation of wall rock stress and pore water pressure in different conditions of seepage path.} \]

\[ \text{Figure 9: Surface settlements in different conditions of seepage path.} \]
and 10.28% of the total damage area, respectively, and the proportion is relatively small. With the decrease of $H$, the proportion of the area of arched damage area has decreased, and the proportion of area of collapsed area has gradually slowed down. It is concluded that as the loading water pressure position moves down, the maximum proportion of the area gradually changes from the arched area to the collapsed area, and the tunnel surrounding rock becomes difficult to arch under the low water pressure position, which is more likely to collapse.
Figure 11: Final failure shapes and their sketches in different conditions of seepage path.
Laboratory observations indicated that the excavation were systematically investigated in this study.

4. Conclusions

The deformation and failure of soft surrounding rock of tunnel under different groundwater conditions during and after the excavation were systematically investigated in this study. Laboratory observations indicated that

1. The excavation results in the decrease of the radial stress and the increase of the tangential stress in the surrounding rock. The change of the radial stress at the top of the tunnel is obviously larger than that of the two sides, and the closer to the tunnel, the greater the variation range of the radial and tangential stress. The excavation results in surface settlement. The surface settlement is the largest just above the tunnel, and the two sides are consistent and symmetrical. This indicates that the surrounding rock is sensitive to excavation disturbance, especially at the top rock. With the continuous loading of water pressure, the pore water pressure at the top of the tunnel first increased, then decreased, and then increased and tended to be stable. The pore water pressure at the left and right sides of the tunnel showed an increasing trend, and the growth rate gradually slowed down. Moreover, the variation value of pore water pressure in the left side was greater than that of the right side, and the pore water pressure at the right side reached stability before the left side.

2. Under the condition of different seepage paths, the failure law of tunnel is consistent, with the continuous loading of water pressure, seepage channel expanding rapidly, tunnel failure pattern were from stable to partial collapse then arch collapse and finally the total collapse. The damage starts from the left arch and progresses diagonally upwards. The failure of tunnel surrounding rock can be roughly divided into three parts, namely, the excavation disturbance zone caused by the excavation, the arch failure zone caused by the pressure-arch effect, and the wear down area caused by the crack expansion through the surface.

3. Under different seepage path, with the hydraulic loading position deepens, the area enclosed by the curve of surrounding rock stress and pore water pressure decreases gradually and finally becomes more and more close, which indicates that the interaction between pore water pressure and stress is becoming more and more intense. The pore water pressure and stress at the top of the tunnel have the largest variation range, which indicates that the seepage channel is easiest to form at the top of the tunnel, followed by the side where the water pressure is loaded. Due to different seepage path, the corresponding loading water quantity of various collapse forms is different. As the hydraulic loading position deepens, the arch failure zone becomes less, the tunnel surrounding rock is more prone to total collapse. The distance between the two main cracks on the left side becomes smaller, the range of surface settlement on the right side increases, and the maximum horizontal distance between the arch collapse area increases.

4. In the process of tunnel excavation, the redistribution of the stress field induces the damage of surrounding rock and forms the excavation disturbance zone. At the beginning of hydraulic loading, water flows along the cracks in the soil and preliminarily forms seepage channel, water seepage began to appear on the left wall of the tunnel, and cracks appeared at the entrance of the tunnel. At this time, the failure mainly occurred in the excavation disturbance zone. With the increase of water flow mass, water content increased and mechanical properties declined, seepage dragged away particles, resulting in the formation of stable seepage channel. Due to the formation of the seepage channel, pore water pressure will release the energy concentration leading to the sudden changes, thus cause the change of surrounding rock stress. The interaction between the two leads to rock mass destruction, the formation of seepage channel at the top of the tunnel, the loss of sufficient bearing capacity of surrounding rock, and the collapse of the excavation disturbance area and then forming arch failure zone. With the water pressure loading, the collapse mode changes from the arch collapse to the downward sliding mode of the whole rock mass on the upper left, which can extend to the two main cracks on the surface. Therefore, the location of the two main cracks and seepage water at the top of the tunnel should be monitored in construction.

**Data Availability**

The data used to support the findings of this study are available from the corresponding author upon request.
Acknowledgments

Financial support from the Fundamental Research Funds for the Central Universities (2020ZDPYMS25) is sincerely acknowledged.

References

[1] Y. C. Wang, H. W. Jing, H. J. Su, and J. Y. Xie, “Effect of a fault fracture zone on the stability of tunnel-surrounding rock,” International Journal of Geomechanics (ASCE), vol. 17, no. 6, pp. 1–20, 2017.

[2] Y. C. Wang, X. Yin, F. Geng, H. W. Jing, H. J. Su, and R. L. Liu, “Risk assessment of water inrush in karst tunnels based on the efficacy coefficient method,” Polish Journal of Environmental Studies, vol. 26, no. 4, pp. 1765–1775, 2017.

[3] Y. C. Wang, F. S. Meng, F. Geng, H. W. Jing, and N. Zhao, “Investigating water permeation through the soil-rock mixture in underground engineering,” Polish Journal of Environmental Studies, vol. 26, no. 4, pp. 1777–1788, 2017.

[4] Y. C. Wang, F. Chen, X. Yin, and F. Geng, “Study on the risk assessment of water inrush in karst tunnels based on intuitionistic fuzzy theory,” Geomatics, Natural Hazards and Risk, vol. 10, no. 1, pp. 1070–1083, 2019.

[5] H. X. Qin, Optimization of Yudiya Tunnel Dewatering and Analysis of Its Impact on Groundwater Environment, [M.S. thesis], Southwest Jiaotong University, Chengdu, 2016.

[6] L. P. Li, S. C. Li, Y. Zhao et al., “3D geomechanical model for progressive failure progress of weak broken surrounding rock in super large section tunnel,” Chinese Journal of Rock Mechanics and Engineering, vol. 31, no. 3, pp. 550–560, 2012.

[7] Y. Li, J. Wu, and K. Li, “Saturated-unsaturated seepage analysis based on FLAC3D,” Rock and Soil Mechanics, vol. 33, no. 2, pp. 617–622, 2012.

[8] Y. C. Wang, Y. Q. Shang, X. S. Yan, and X. H. Xu, “Study on collapse mechanism in loose wall rock of shallow tunnel under rainfall,” Journal of Harbin Institute of Technology, vol. 44, no. 2, pp. 142–148, 2012.

[9] Y. Wang and J. Liu, “Inverse analysis of fully coupled dynamic water flow and stress in fractured rock masses,” Chinese Journal of Rock Mechanics and Engineering, vol. 27, no. 8, pp. 1652–1658, 2008.

[10] Y. C. Wang, H. W. Jing, L. J. Han, L. Y. Yu, and Q. Zhang, “Risk analysis on swell–shrink capacity of expansive soils with efficacy coefficient method and entropy coefficient method,” Applied Clay Science, vol. 99, pp. 275–281, 2014.

[11] Y. C. Wang, H. W. Jing, L. Y. Yu, H. J. Su, and N. Luo, “Set pair analysis for risk assessment of water inrush in karst tunnels,” Bulletin of Engineering Geology and the Environment, vol. 76, no. 3, pp. 1199–1207, 2017.

[12] X. Tan, Study on Mechanical Effects of Underwater Tunnel Construction Considering Fluid-Solid Coupling Effects, [M.S. thesis], Central South University, Changsha, 2009.

[13] S. P. Neuman, “Saturated-unsaturated seepage by finite elements,” Journal of the Hydraulics Engineering, vol. 99, no. 12, pp. 2233–2250, 1973.

[14] L. Y. Yu, Study on Stability of Surrounding Rocks and Selection of Overburden Thickness for Underwater for Underwater Tunnels, [Ph.D. thesis], Shandong University, Jinan, 2010.

[15] H. Wang, C. Y. Lu, D. Y. Qin, X. F. Sang, Y. Li, and W. H. Xiao, “Advances in method and application of groundwater numerical simulation,” Earth Science Frontiers, vol. 17, no. 6, pp. 1–12, 2010.

[16] P. J. Closmann, “An aquifer model for fissured reservoirs,” Society of Petroleum Engineers Journal, vol. 15, no. 5, pp. 385–389, 1975.

[17] L. Lam, D. G. Fredlund, and S. L. Barrou, “Transient seepage model for saturated-unsaturated soil systems: a geotechnical engineering approach,” Canadian Geotechnical Journal, vol. 24, no. 4, pp. 565–580, 1987.

[18] M. Grenon, C. Bruneau, and I. Kapiniga Kalala, “Quantifying the impact of small variations in fracture geometric characteristics on peak rock mass properties at a mining project using a coupled DFN-DEM approach,” Computers and Geotechnics, vol. 58, pp. 47–55, 2014.

[19] H. M. Chen, H. S. Yu, and M. J. Smith, “Physical model tests and numerical simulation for assessing the stability of bricklined tunnels,” Tunnelling and Underground Space Technology, vol. 53, pp. 109–119, 2016.

[20] A. Osouli and B. M. Bajestani, “The interplay between moisture sensitive roof rocks and roof falls in an Illinois underground coal mine,” Computers and Geotechnics, vol. 80, pp. 152–166, 2016.

[21] S. Shreedharan and K. PHSW, “Discontinuum-equivalent continuum analysis of the stability of tunnels in a deep coal mine using the distinct element method,” Rock Mechanics and Rock Engineering, vol. 49, no. 5, pp. 1903–1922, 2016.

[22] D. Y. Li, X. B. Li, W. Zhang, F. Q. Gong, and B. R. Huang, “Stability analysis of surrounding rock of multi-arch tunnel based on coupled fluid-solid theorem,” Chinese Journal of Rock Mechanics and Engineering, vol. 26, no. 5, pp. 1056–1064, 2007.

[23] C. Wolkersdorfer, R. Bowell, J. M. Azmazaga et al., “Contemporary reviews of mine water studies in Europe,” Mine Water and the Environment, vol. 12, no. 3, p. 236, 2004.

[24] H. W. Rauch and W. B. White, “Lithologic controls on the development of solution porosity in carbonate aquifers,” Water Resources Research, vol. 6, no. 4, pp. 1175–1192, 1970.

[25] N. Barton, S. Bandis, and K. Bakhtiar, “Strength, deformation and conductivity coupling of rock joints,” International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, vol. 22, no. 3, pp. 121–140, 1985.

[26] T. Oda, T. Takemura, and T. Aoki, “Damage growth and permeability change in triaxial compression tests of Inada granite,” Mechanics of Materials, vol. 34, no. 6, pp. 313–331, 2002.

[27] G. Archambault, S. Poirier, A. Rouleau, S. Gentier, and J. Riss, “The behavior of induced pore fluid pressure in undrained triaxial shear test on fragmented porous analog rock material specimens,” in Mechanics of Jointed and Faulted Rock, Part 11, Chapter 85, Rossmanich: Balkeman, 1998.

[28] P. Valko and M. J. Economides, “Propagation of hydraulically induced fractures—a continuum damage mechanics approach,” International Journal of Rock Mechanics and Mining Sciences, vol. 31, no. 3, pp. 221–229, 1994.

[29] B. Amadei and T. Illangasekare, “A mathematical model for flow and solute transport in non-homogeneous rock
fractures,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 31, no. 6, pp. 719–731, 1994.

[30] Q. Y. Zhang, X. T. Zhang, Z. C. Wang, W. Xiang, and J. H. Xue, “Failure mechanism and numerical simulation of zonal disintegration around a deep tunnel under high stress,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 93, pp. 344–355, 2017.

[31] W. Chen, H. N. Yan, and H. N. Zhang, “Influence of rainfall seepage on the behavior of an unevenly-pressured shallow tunnel and its support system,” *Modern Tunnel Technology*, vol. 45, no. 1, pp. 30–38, 2008.

[32] M. Pesendorfer and S. Loew, “Subsurface exploration and transient pressure testing from a deep tunnel in fractured and karstified limestones (Lotschberg Base Tunnel Switzerland),” *International Journal of Rock Mechanics and Mining Sciences*, vol. 47, no. 1, pp. 121–137, 2010.

[33] H. P. Kang, J. Z. Li, J. H. Yang, and F. Q. Gao, “Investigation on the influence of abutment pressure on the stability of rock bolt reinforced roof strata through physical and numerical modeling,” *Rock Mechanics and Rock Engineering*, vol. 50, no. 2, pp. 387–401, 2017.

[34] Z. F. Zhou, Z. Wang, S. J. Li, Q. Shen, M. Chen, and H. Zheng, “Determination of nonlinear seepage slope for dislocation interface by in situ tests,” *Bulletin of Engineering Geology and the Environment*, vol. 80, no. 3, pp. 2765–2775, 2021.

[35] J. F. Hou, Z. P. Guo, J. B. Li, and L. J. Zhao, “Study on triaxial creep test and theoretical model of cemented gangue-fly ash backfill under seepage-stress coupling,” *Construction and building materials*, vol. 273, article 121722, 2020.

[36] Q. Sun, G. H. Meng, K. Sun, and J. X. Zhang, “Physical simulation experiment on prevention and control of water inrush disaster by backfilling mining under aquifer,” *Environmental Earth Sciences*, vol. 79, no. 18, 2020.

[37] C. B. Wang, “Study on the Progressive Failure Mechanism of the Surrounding Rock of Tunnel Constructed in Soft Rock,” [Ph.D. thesis], Tongji University, Shanghai, 2007.

[38] H. Q. Li, “Mechanism of highway flood damage and decision system research,” [Ph.D. thesis], Zhejiang University, Hangzhou, 2008.

[39] Y. C. Wang, “Collapse mechanism and preventive measures of mountain tunnel,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 30, no. 11, p. 2376, 2011.

[40] S. C. Li, S. G. Song, L. P. Li et al., “Development on subsea tunnel model test system for solid-fluid coupling and its application,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 32, no. 5, pp. 883–890, 2013.

[41] D. M. Wang, Q. S. Zhang, X. Zhang, K. Wang, and Y. H. Tan, “Model experiment on inrush of water and mud and catastrophic evolution in a fault fracture zone tunnel,” *Rock and Soil Mechanics*, vol. 37, no. 10, pp. 2851–2860, 2016.

[42] Y. Zhou, S. C. Li, L. P. Li et al., “3D fluid-solid coupled model test on water-inrush in tunnel due to seepage from filled karst conduit,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 34, no. 9, pp. 1739–1749, 2015.

[43] X. Yang, C. Y. Zhou, Z. Liu, D. L. Su, and Z. C. Du, “Model tests for failure mechanism of typical soft rock slopes of red beds under rainfall in South China,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 35, no. 3, pp. 549–557, 2016.

[44] Y. F. Li, L. M. Peng, Y. H. Zhang, G. F. Huang, and M. F. Lei, “Calculations of surrounding rock pressures of shallow buried tunnels under linear and nonlinear failure criteria,” *Modern Tunnelling Technology*, vol. 50, no. 5, pp. 68–74, 2013.

[45] P. Chen, *Study on Stability of Tunnel Surrounding Rock Based on Complex Function Method and Catastrophe Theory*, [M.S. thesis], Beijing Jiaotong University, Beijing, 2014.

[46] Q. J. Zuo, L. Wu, Z. L. Lu, Y. Z. Tan, and Q. Yuan, “Instability analysis of soft surrounding rock in shallow tunnel portal under unsymmetrical pressure by catastrophe theory,” *Rock and Soil Mechanics*, vol. 36, no. S2, pp. 424–430, 2015.