Prediction of water inflow into a tunnel based on three-district zoning of faults

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Abstract. Water inflow into a tunnel subject to fault zones and fault effective zones is interpreted in this study using a three-district zoning method. An improved Brinkman model is proposed to investigate the seepage law of the geological defects of a fault. A coupled calculation model of typical Darcy seepage and Brinkman rapid seepage is constructed to establish a mathematical model of nonlinear seepage flow based on three-district zoning and the corresponding numerical implementation. In addition, the influence of the angle between the fault dip and tunneling directions on the water inrush in a tunnel is also studied. The variation characteristics of the pore pressure and velocity fields under various construction stages are analyzed, as is the seepage velocity of pore water at the tunnel heading. Moreover, the effects of the fault dip direction on the seepage field and water inflow are discussed. The following results were obtained. (1) Before excavation to the fault effective zone, the pore pressure at the same depth remained essentially unchanged in front of the tunnel heading. After excavation to the fault effective zone, the pore pressure at the same depth increases linearly with distance in front of the tunnel heading. (2) The seepage velocity changed gently before excavation to the fault effective zone but showed wavy fluctuating after excavation to the fault effective zone. The velocity reached its maximum value in the fault zone before decreasing rapidly and remaining close to zero in the general surrounding rock zones. (3) As the excavation length increased, the water inflow increased gradually, reaching its maximum value in the fault zone. (4) In the fault zone, the seepage velocity decreased with an increase in the fault dip. The water inflow reached maximum and minimum values at angles of 90° and 150°, respectively.

Key words: three-district zoning; tunnel fault; water inflow
1. Introduction

In tunnel construction projects, the abrupt occurrence of water inrush is among the most commonly encountered geologic disasters \cite{1-3}. This unexpected surge of water can lead to disastrous effects such as human fatalities and severe damages or destruction of the tunnel structure and excavation equipment \cite{4-7}. Therefore, forecasting water inflow has become a key research area of great concern to scholars in the field of tunnel engineering and is a particularly critical issue affecting tunnel construction. Over the past 50 years, researchers and engineering professionals in the international community have conducted extensive exploration, testing, and theoretical investigations to predict water inflow in tunnels. Such research has enabled the forecasting of water inflow and the identification of water inrush locations to evolve from qualitative to quantitative stages \cite{8-12}.

According to the classification by Meng \cite{13}, the methods for predicting subsurface water inflow can be categorized into two types: long-term water inflow forecast models including deterministic and stochastic forecast models and short-term water inrush models including numerical simulation, empirical modeling, and probabilistic assessment of water inrush incidents. Numerous studies have been conducted using these methods. Wang \cite{14} used scale model testing and numerical simulation to analyze the seepage flow field in undersea tunnels and conducted numerical analysis to predict the water inflow in tunnels. Ivars \cite{15} employed the finite element method to investigate the water inflow issue that occurs during the excavation of fractured formations. Marinelli and Niccoli \cite{16} proposed a set of simplified equations to predict water inflow in underground mines. Lin \cite{17} developed a new spiral variable-section capillary model for calculating the critical hydraulic gradient of water inrush in tunnels. Shi \cite{18} utilized the hydraulic theory to analyze the water flux at water inrush points. Hwang and Lu \cite{19} proposed a semi-empirical formula for calculating the water inrush in tunnels. According to the development characteristics of a karst pipeline water inrush tunnel area, Ni\cite{20} and Wang\cite{21} equalized the flow in the void to the whole rock mass based on the continuum theory. Pan\cite{22} proposed a new method for the preparation of modeled karst caverns filled with confined water. In addition to the above research, several scholars attempted to apply theories based on nonlinear and fuzzy mathematics in their prediction of water inflow in tunnels \cite{23-27}. These new techniques and methods have significantly enhanced the accuracy in predicting unsteady-state tunnel water inflow in porous media and fractured media under complex boundary conditions. However, these methods fail to solve the problem concerning the coupling between laminar flow and turbulent flow in highly heterogeneous karst rock formations. Thus, a mature theory and a commonly accepted calculation methodology with accepted accuracy for predicting tunnel water inflow is needed.

During construction in karst tunnels, water inrush, including that induced by faults, often occurs in the subsurface, which poses a significant threat to the tunnel construction and the safety of workers \cite{28-31}. Therefore, a reliable prediction of water inflow in karst tunnels is of great importance to reduce such risk and ensure normal tunnel construction. The present study employs the improved Brinkman equation to examine the water flow patterns in fault and fault effective zones. In addition, a computational model is established that couples the classical Darcy seepage flow with the Brinkman high-velocity seepage flow. Moreover, a mathematical model is proposed to describe the nonlinear water inflow seepage rate based three-district zoning of a fault, and a numerical simulation methodology is applied to further study the impact of fault dip direction on the water inflow in tunnels. The conclusion drawn in the present study can be leveraged to provide guidance in research
concerning the prediction of water inrush in karst tunnels.

2. Conceptual model of three-district zoning of water inflow into a tunnel
Based on the computational principle associated with the tunnel structure and the relevant field experiences derived from case studies, water inflow into a tunnel subject to a fault zone and fault effective zones is interpreted using a three-district zoning method. The present study devises a geometric model for conducting numerical simulation. The overall model design based on a fault dip direction of 60° is illustrated in Figure 1.

The model extends 1000 m and 300 m along the positive horizontal (x-axis) and vertical directions (y-axis), respectively. The tunnel is 10 m in height, ranging from 145 m to 155 m on the y-axis. The tunnel’s centerline is located on a straight line corresponding to \( y = 150 \) m. Zones A, B and C are a regular surrounding rock zone, fault effective zone, and fault zone, respectively. The fault effective zones are located symmetrically on both sides of the fault zone, whereas B1 and B2 denote the boundaries of the fault effective zone and the regular surrounding rock zone. During the numerical simulation, the tunnel’s excavation length, fault zone width, fault effective zone width, and fault dip direction can be adjusted in accordance with the simulation conditions, whereas the coordinates of the fault zone’s center, i.e., (500, 150), remain unchanged.

The following simulation parameters include water density of 1000 kg/m\(^3\) and viscosity of 0.001 Pa \cdot s. The porosity of the fault zone and the surrounding rock in the fault effective zone was set to 0.5. The permeability of the regular surrounding rock was \( 10^{-12} \) m\(^2\), and that of the surrounding rock in the fault zone was set according to the simulation conditions. The permeability of the surrounding rock in the fault effective zone does not have a fixed value; rather, it is subject to a nonlinear evolution process. That is, the permeability evolves smoothly from the fault zone to the regular surrounding rock; the corresponding method for setting the parameters is described in detail in subsequent sections of the present study. Moreover, because water is an incompressible adiabatic fluid, the simulation was based on steady-state analysis.

3. Computational model of three-district zoning of water inflow into a tunnel
An improved Brinkman model is proposed to investigate the seepage law of the geological defects of a fault. The numerical model is based on three-district zoning of a fault zone and fault effective zones. (1) Darcy seepage flow zone
In Figure 1, zone A consists of regular surrounding rock. The water in the pore space and the nearby surrounding rock is subject to a stable stress field and can be modeled as seepage flow in low-velocity porous media, which is primarily governed by a pressure-driven mechanism. Thus, the inertial force of fluid can be neglected. Therefore, the system can be described by a Darcy seepage flow equation.
That is, the flow regime associated with the pore water at this stage can be described by the following Darcy equation:

\[ \nabla \cdot \left[ \frac{(k/\eta)(\nabla p + \rho g \nabla D)}{\eta} \right] = 0. \]  

(1)

Regarding the boundary conditions, the model’s upper boundary and sidewalls on both sides allow the inflow of water, which serve as the source of the water supply. Because precipitation supplies sufficient water, and the water inlet boundary is assigned the pressure boundary condition, the following condition should be satisfied:

\[ p = p_0. \]  

(2)

The model’s upper boundary was set to be a free water surface, in which the pore water pressure was set to zero. The water pressure gradually increases from top to bottom at the sidewalls on both sides; that at the bottom was \( 3 \times 10^6 \) Pa. Moreover, the tunnel heading makes contact with the atmosphere, the pore water pressure of which was also set to zero.

The side boundary of the excavation zone as well as the bottom boundary of zone A are impermeable to water and therefore need to satisfy the following condition:

\[ \nabla \cdot \left[ \frac{(k/\eta)(\nabla p + \rho g \nabla D)}{\eta} \right] = 0. \]  

(3)

(2) Improved Brinkman high-velocity flow zone

In Figure 1, zone B is a fault effective zone, whereas zone C is a fault zone. In these two zones, as the pore water flows at a high velocity, the resulting strong shear effect leads to amplified energy dissipation, making it inappropriate to neglect the shear stress associated with viscous flow. For this reason, the Brinkman equation should be employed to describe the flow field. Specifically, the flow regime associated with the pore water at this stage can be described using the following Brinkman equation:

\[ \frac{(\eta/k)x}{\nabla \cdot \left[ \frac{(k/\eta)(\nabla p + \rho g \nabla D)}{\eta} \right]} = F. \]  

(4)

Assuming that the fault zone’s permeability \( k = k_0 = 10^{-a} \text{ m}^2 \), and the centerline of the fault zone corresponds to \( Ax + By + C = 0 \), the permeability of the fault effective zone can be expressed as

\[ \ln k = \left[ a + \frac{12 - a}{l} \left( \frac{Ax + By + C}{\sqrt{A^2 + B^2}} - \frac{d}{2} \right) \right]. \]  

(5)

By plugging equation (5) into equation (4), a Brinkman equation-based mathematical model can be established for simulating single-fault nonlinear seepage flow. In this case, the upper boundaries associated with zones B and C satisfy equation (6), whereas the lower boundaries satisfy equation (7).

\[ \nabla \cdot \left[ \frac{(k/\eta)(\nabla p + \rho g \nabla D)}{\eta} \right] = 0 \]  

(6)

\[ u = 0 \]  

(7)

(3) Transition zone

For pore water, the flow regime transition from the fault effective zone to the regular surrounding rock needs to satisfy certain transition conditions. Based on mass conservation and pressure equilibrium,
the Darcy seepage flow can be coupled with the Brinkman high-velocity flow to form a unified flow field. Specifically, both the pressure and flow velocity changes need to be continuous across the interface between the Darcy seepage flow zone and the Brinkman high-velocity flow zone.

\[
\begin{align*}
    p_D(B_1) &= p_B(B_1) \quad \text{(8)} \\
    u_D(B_1) &= u_B(B_1)
\end{align*}
\]

By solving equations (1)–(9), i.e., the seepage flow equations and the associated boundary conditions, the three-zone nonlinear seepage flow numerical model can be simultaneously obtained on the basis of mass conservation and the pressure equilibrium of fluid. Through numerical calculation, the two physical processes in the three-zone model can be simulated, corresponding to Darcy seepage flow and Brinkman high-velocity flow, respectively. As a result, numerical simulation can be conducted for nonlinear seepage flow pertaining to the water inrush process in a fault zone. The present study employs COMSOL Multiphysics software to implement the aforementioned modeling strategy.

4. Numerical results and analysis

To study the impact of fault dip direction on tunnel water inflow, it is assumed that the width \(d\) of the fault zone (zone C) is 10 m; the width \(l\) of the fault effective zone (zone B) is 10 m; and the permeability \(k\) of the fault zone (zone C) is \(10^{-8}\) m². On the basis of these settings, the fault dip directions were set to 30°, 60°, 90°, 120°, and 150°, respectively. For each fault dip direction, five operation cases were used for simulating the excavation process: (1) Case 1: The tunnel is excavated to 10 m ahead of the left fault effective zone; (2) Case 2: the tunnel is excavated to the center of the left fault effective zone; (3) Case 3: the tunnel is excavated to the center of the fault zone; (4) Case 4: the tunnel is excavated to the center of the right fault effective zone; (5) Case 5: the tunnel is excavated to 10 m behind the right fault effective zone.

4.1 Analysis of seepage flow field

In this section, the fault dip direction \(\alpha = 30^\circ\) is used to analyze the seepage field, and the five different excavation conditions are numerically simulated.

4.1.1 Case 1 (\(x = 451.35\) m)

(1) Simulation results

As the tunnel was excavated to 10 m ahead of the left fault effective zone, corresponding to an excavation length of 451.35 m, the variation in pore water pressure and velocity fields in the surrounding rock was noted, as shown in Figure 2.
(2) Analysis of seepage field

To visually represent the variation in the pore water pressure and velocity fields, five probe lines were placed for analysis. The locations of the probe lines and the quantity of points are listed in Table 1.

| No. | Probe line range                  | Number of probe points |
|-----|-----------------------------------|------------------------|
| N1  | \( x = 451.35 - 551.35 \text{ m}, y = 130 \text{ m} \) | 1000                   |
| N2  | \( x = 451.35 - 551.35 \text{ m}, y = 140 \text{ m} \) | 1000                   |
| N3  | \( x = 451.35 - 551.35 \text{ m}, y = 150 \text{ m} \) | 1000                   |
| N4  | \( x = 451.35 - 551.35 \text{ m}, y = 160 \text{ m} \) | 1000                   |
| N5  | \( x = 451.35 - 551.35 \text{ m}, y = 170 \text{ m} \) | 1000                   |

The pore water pressure and velocity curves for the five probe lines are illustrated in Figure 3.
As shown in Figure 3(a), the pressure increased gradually before entering the left fault effective zone and increased continually in a short distance after entering the zone. Then, the pressure increased gently to a constant status, where a larger $y$ value relates to a smaller corresponding pressure.

As shown in Figure 3(b), the seepage velocity was less variable before entering the left fault effective zone and exhibited wavy fluctuation within the zone. The seepage velocity increased rapidly near the fault zone, peaked within it, and then decreased rapidly to zero in the right fault effective zone. The seepage velocity remained at zero and can thus be neglected in the regular surrounding rock. In this case, a larger the $y$ value relates to a larger corresponding velocity in the fault.

(3) Analysis of water inflow at tunnel heading

To analyze the water inflow at the tunnel heading, a probe line was placed along the tunnel heading height ($x = 451.35, y = 145–155$) to study the variation in seepage velocity. Figure 4 shows the seepage velocity of the pore water along the $x$-direction at the tunnel heading.

As shown in the figure, when the tunnel heading height remained between 0 m and 1.16 m, the seepage velocity decreased gradually and reaches its maximum, i.e., 0.001 m/s, at a height of 0 m. When the tunnel heading height was 1.16–9.35 m, the seepage velocity changed slowly by first decreasing and then increasing, reaching its minimum value of $1.45 \times 10^{-4}$ m/s at a height of 6 m. When the height was 9.35–10 m, the seepage velocity increased gradually and peaked at $5.54 \times 10^{-4}$ m/s at a height of 10 m.
Overall, the seepage velocity peaked at the bottom of the tunnel heading and then gradually decreased along the height direction. The seepage velocity changed slowly near the middle and then increased gradually again near the top of the tunnel heading.

4.1.2 Case 2 ($x = 471.35$ m)

(1) Simulation results

As the tunnel was excavated to the center of the left fault effective zone, corresponding to an excavation length of 471.35 m, the variation in pore water pressure and velocity fields in the surrounding rock was noted, as shown in Figure 5.

(2) Analysis of water inflow at tunnel heading

To analyze the water inflow at the tunnel heading, a probe line was placed along the tunnel heading height ($x = 471.35$, $y = 145–155$) to study the variation in seepage velocity. The seepage velocity of the pore water along the $x$-direction at the tunnel heading is shown in Figure 6.
As shown in the figure, when the tunnel heading height remained between 0 m and 0.25 m, the seepage velocity increased rapidly and reached its maximum value of 0.076 m/s at a height of 0.25 m. When the tunnel heading height was 0.25–10 m, the seepage velocity decreased rapidly and plunged to zero at a height of 5.58 m. Overall, the seepage velocity peaked at the bottom of the tunnel heading and then gradually decreased along the height direction before dropping to zero at the middle height of the tunnel heading.

4.1.3 Case 3 (x = 491.35 m)

(1) Simulation results

As the tunnel was excavated to the center of the fault zone, corresponding to an excavation length of 491.35 m, the variation in pore water pressure and velocity fields in the surrounding rock was noted, as illustrated in Figure 7.

(2) Analysis of water inflow at tunnel heading

To analyze the water inflow at the tunnel heading, a probe line was placed along the tunnel heading height (x = 491.35, y = 145–155) to study the variation in seepage velocity. The seepage velocity of the pore water along the x-direction at the tunnel heading is shown in Figure 8.
As shown in the figure, when the tunnel heading height remained between 0 m and 0.8 m, the seepage velocity increased rapidly and reached its maximum value of 0.171 m/s at a height of 0.8 m. When the tunnel heading height was 0.8–6.13 m, the seepage velocity decreased slowly, approaching zero at a height of 6.13 m. When the tunnel heading height was 6.13–10 m, the seepage velocity first increased then decreased, plunging to zero at a height of 10 m.

Overall, the seepage velocity peaked at the bottom of the tunnel heading and then gradually decreased along the height direction. The seepage velocity dropped to zero at the top of the tunnel heading.

### 4.1.4 Case 4 \((x = 511.35 \text{ m})\)

#### (1) Simulation results

As the tunnel was excavated to the center of the right fault effective zone, corresponding to an excavation length of 511.35 m, the variation in pore water pressure and velocity fields in the surrounding rock was noted, as illustrated in Figure 9.

#### (2) Analysis of water inflow at tunnel heading

To analyze the water inflow at the tunnel heading, a probe line was placed along the tunnel heading height \((x = 511.35, y = 145–155)\) to study the variation in seepage velocity. The seepage velocity of
the pore water along the x-direction at the tunnel heading is shown in Figure 10.

As shown in the figure, when the tunnel heading height remained between 0 m and 5.6 m, the seepage velocity increased rapidly and reached its maximum value of 0.113 m/s at a height of 5.6 m. When the tunnel heading height was 5.6 m–9.35 m, the seepage velocity decreased slowly. At 9.35 m–10 m, the seepage velocity first increased then rapidly decreased, plunging to zero at a height of 10 m. Overall, the seepage velocity was zero at the bottom of the tunnel heading and then gradually increased along the height direction to peak at the middle height. Then, the velocity gradually decreased and again dropped to zero at the top of the tunnel heading.

4.1.5 Case 5 (x = 531.35 m)
(1) Simulation results
As the tunnel was excavated to 10 m behind the right fault effective zone, corresponding to an excavation length of 531.35 m, the variation in pore water pressure and velocity fields in the surrounding rock was noted, as illustrated in Figure 11.

(2) Analysis of water inflow at tunnel heading
To analyze the water inflow at the tunnel heading, a probe line was placed along the tunnel heading
height \((x = 531.35, y = 145–155)\) to study the variation in seepage velocity. The seepage velocity of the pore water along the \(x\)-direction at the tunnel heading is shown in Figure 12.

Figure 12. \(X\)-velocity of pore water on the tunnel face with excavation to 531.35 m

As shown in the figure, when the tunnel heading height remained between 0 m and 0.55 m, the seepage velocity gradually decreased. With a tunnel heading height of 0.55–9.2 m, the velocity changed slowly from decreasing to increasing and reached its minimum value of \(1.13 \times 10^{-4}\) m/s at 4 m. When the tunnel heading height was 9.2–10 m, the seepage velocity increased gradually, peaking at \(1.5 \times 10^{-3}\) m/s at a height of 10 m.

Overall, the seepage velocity showed significant variation near the bottom and top of the tunnel heading; negligible variation occurred in the middle area. The peak value was reached the top of the tunnel heading.

4.2 Discussion

4.2.1 Analysis of seepage field under various fault dip directions

To analyze the effects of the dip direction on the seepage field, the present study investigated the variation in the seepage field within 100 m in front of the tunnel heading for five different fault dip directions when the tunnel was excavated to 10 m ahead of the left fault effective zone. For the five different height values on the \(y\)-axis, a probe line at \(y = 150\) m was placed to obtain the pore water pressure and velocity curves for various dip directions, as shown in Figure 13.

Figure 13. Pressure and velocity curves within 100 m in front of the tunnel face under various fault dip values

(1) As shown in Figure 13(a), the pressure increased gradually before entering the left fault effective
zone. Afterward, the first pressure increased and then showed slow variation, which is plotted roughly as a straight horizontal line in the figure. The fault dip directions of 60° and 150° corresponded to the maximum and minimum pressures, respectively. For the three intermediate dip directions, i.e, 90°, 120°, and 30°, the pressure decreased.

(2) As shown in Figure 13(b), the seepage velocity decreased gradually before entering the left fault effective zone and exhibited wavy fluctuation within the zone. Among the five different fault dip directions, 90° and 150° corresponded to the peak and minimal flow velocities, respectively. With intermediate values of 120°, 60°, and 30°, the seepage velocity decreased monotonically with an increase in the fault dip direction within the fault zone. That is, the seepage velocity peaked when the fault dip direction was 30° dropped to its minimum value when the fault dip direction was 150°. Within the right fault effective zone, the seepage velocity dropped rapidly and approached zero in the middle area of the fracture zone. Afterward, the seepage velocity remained close to zero; therefore, it can be neglected in the regular surrounding rock behind the fracture zone.

4.2.2 Analysis of water inflow at tunnel heading for various fault dip directions

Among the five different fault dip directions, the variation in maximum seepage velocity along the \( x \)-direction and the corresponding water inflow for the five different excavation distances are shown in Table 2. The corresponding water inflow variation curve is illustrated in Figure 14.

Table 2. Maximum \( x \)-velocity and water inflow on the tunnel face under various excavation positions.

| X-velocity and water inflow | Fault dip direction \( \alpha/° \) | Excavation position |
|-----------------------------|---------------------------------|--------------------|
|                             | \( U_{\text{max}}/(\times 10^{-3} \text{m/s}) \) | 1  | 2  | 3  | 4  | 5  |
| 30                          | 1.05                           | 76.3             | 1.71 | 113 | 1.51 |
| 60                          | 0.92                           | 66.3             | 2.07 | 178 | 0.71 |
| 90                          | 0.38                           | 46.5             | 1.94 | 11  | 0.72 |
| 120                         | 0.78                           | 87.9             | 1.62 | 6.7 | 0.57 |
| 150                         | 0.71                           | 78.6             | 1.07 | 79  | 0.86 |
|                             | \( Q/(\times 10^{-2} \text{m}^3\text{ s}^{-1}) \) | 30             | 0.22011 | 7.4202 | 0.48017 | 49.545 | 0.17703 |
| 60                          | 0.20359                        | 18.614           | 1.0336 | 32.247 | 0.14259 |
| 90                          | 0.18854                        | 36.279           | 1.1055 | 2.984 | 0.12251 |
| 120                         | 0.1.9441                       | 21.669           | 0.76366 | 1.653 | 0.11983 |
| 150                         | 0.2.1178                       | 7.7199           | 0.41241 | 27.371 | 0.11827 |

Note: The excavation positions are described as follows: 1. The tunnel is excavated to 10 m ahead of the left fault effective zone; 2. The tunnel is excavated to the center of the left fault effective zone; 3. The tunnel is excavated to the center of the left fault area; 4. The tunnel is excavated to the center of the right fault effective zone; 5. The tunnel is excavated to 10 m behind the right fault effective zone.
Figure 14. Change curves of water inflow on the tunnel face under various excavation positions

Table 2 and Figure 14 show the results of the five cases, as summarized below. 1) When the tunnel was excavated to 10 m ahead of the left fault effective zone, the water inflow was relatively low at the tunnel heading. Among the five fault dip directions, 30° and 90° corresponded to the maximum and minimum water inrush, respectively. The water inflow decreased gradually in sequence at dip directions of 150°, 60°, and 120°. 2) The water inflow at the tunnel heading increased when the tunnel was excavated to the center of the left fault effective zone. Among the five fault dip directions, 90° and 30° corresponded to the peak and minimum water inflow, respectively. The inflow decreased sequentially at dip directions of 120°, 60°, and 150°. 3) The water inflow peaked at the tunnel heading when the tunnel was excavated to the middle area of the fault zone. Among the five fault dip directions, 90° and 150° corresponded to the peak and minimum water inflow, respectively. The water inflow decreased sequentially at dip directions of 60°, 120°, and 30°. 4) The water inflow at the tunnel heading decreased when the tunnel was excavated to the center of the right fault effective zone. Among the five fault dip directions, 30° and 120° corresponded to the peak and minimum water inflow, respectively. The inflow decreased sequentially at dip directions of 60°, 150°, and 90°. 5) The water inflow was relatively low at the tunnel heading when the tunnel was excavated to 10 m behind the right fault effective zone. Among the five fault dip directions, 30° and 150° corresponded to the peak water and minimum water inflow. The inflow decreased sequentially at dip directions of 60°, 90°, and 120°.

Overall, the water inflow at the tunnel heading gradually increased with the tunnel excavation length, which peaked in the fault zone and then gradually decreased. Moreover, the water inflow was relatively low at the tunnel heading within the regular surrounding rock.

5. Conclusions

The improved Brinkman equation is proposed to investigate the flow pattern of water in a formation with geologic defects such as fault zones and fault effective zones. Furthermore, a numerical simulation model coupling the classical Darcy seepage flow model and the Brinkman high-velocity seepage flow model is established to create a mathematical model for nonlinear seepage flow based on three-district zoning of a fault. The corresponding methodology for building the numerical model studied to evaluate the effects of fault dip direction on tunnel water inflow. The present study examines in detail the characteristics concerning the variation in the pore water pressure and velocity fields in front of the tunnel heading under various excavation conditions as well as the variation in seepage velocity associated with the pore water at the tunnel heading. Finally, the influence of fault dip direction on the tunnel seepage flow field and the water inflow is discussed. The following conclusions were drawn.

1) Prior to the tunnel excavation, the initial pore water pressure distributions in the surrounding rock, the fault effective zone, and the fault zone exhibited similar patterns, i.e., the pore water pressure increased with the depth. After the excavation, the pore water pressure field in the surrounding rock exhibited significant variation. In addition, the contours of the pore water pressure near the tunnel exhibited dense distribution, and the water pressure was relatively low, giving rise to a funnel-shaped low-pressure zone. Moreover, as the tunnel was excavated to the fault effective zone, the pore water pressure reduced substantially. Compared with that in the regular surrounding rock, the low-pressure...
zone was further expanded.

(2) Before the excavation front reached the fault effective zone, the pore water pressure at the same depth in front of the tunnel heading remained roughly unchanged with an increase in distance. After the front reached the fault effective zone, the pore water pressure at the same depth in front of the tunnel heading followed a linear increase with distance.

(3) Before the excavation front reached the left fault effective zone, the seepage velocity exhibited a slow variation. After the excavation progressed into the fault effective zone, the seepage velocity exhibited wavy fluctuation. In addition, the seepage velocity increased abruptly near the fault zone and peaked within it before decreasing rapidly in the right fault effective zone and dropping to zero in the middle area. Therefore, the seepage velocity can be safely neglected in the surrounding rock region.

(4) In the left fault effective zone and the surrounding rock zone, among the five fault dip directions, 60° and 150° corresponded to the peak and minimum values of pore water pressure.

(5) In the left fault effective zone, among the five fault dip directions, 90° and 150° corresponded to the peak and minimum flow velocities. In the fault zone, the seepage velocity decreased monotonically with an increase in the fault dip direction, i.e., 30° and 150° corresponded to the peak and minimum flow velocities, respectively.

(6) Before the excavation front reached the fault zone, the water inflow at the tunnel heading gradually increased and peaked in the fault zone before gradually decreasing. In the regular surrounding rock region, the water inflow was fairly low at the tunnel heading.

(7) In the fault zone, among the five fault dip directions, 90° and 150° corresponded to the peak and minimum water inflow, respectively.

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