When the deep tunnel is excavated, the pressure of the confined water is relatively high, causing the water inrush to have a hydraulic fracturing effect. The method of theoretical analysis was adopted to study this effect. A mechanical model for fracturing water inrush under blasting excavation conditions was established. The water inrush under this condition is the result of the combined action of static load (water pressure and in situ stress) and dynamic load (explosive stress wave). According to whether the normal stress on the hydraulic crack surface was tensile stress or compressive stress, two types of water inrush were proposed: water inrush caused by tensile-shear damage and water inrush caused by compression-shear damage. These two types of critical water pressures were calculated separately. The relationship between critical water pressure, in situ stress, and blasting disturbance load was given, and a pore water pressure splitting factor was introduced in the calculation process. The theoretically obtained critical water pressure had been verified in the case of water inrush in a deep-buried tunnel. The established theory can guide field practice well.

1. Introduction

After mining or tunnel engineering enters deep [1–3], the rock mass often has the characteristics of high water pressure and high in situ stress [4], which is prone to water inrush geological disasters. The water inrush of these rock mass projects has a hydraulic fracturing effect [5, 6]. During tunnel excavation, high water pressure is the basic condition for water inrush channel, and excavation disturbance is the inducing factor of water inrush [7]. Excavation breaks the original balance of the system [8, 9] and is a necessary condition for water inrush. The combined action of the two causes the microcracks in the rock [10] mass to initiate, expand, and penetrate. Finally, a water inrush channel is formed, causing water inrush.

In coal mining, hydraulic fracturing water inrush mainly includes two types: floor fracturing water inrush and karst collapse column fracturing water inrush. When the water pressure in the floor is high, the water pressure in the confined aquifer has a fracturing and expansion effect on the water-resistant rock mass, which can cause the primary fissures in the water-resistant rock mass to open and expand [11], thereby reducing the strength of the water-resistant rock [12]. The water rises up along the cracks in the floor. During the ascending process, the water pressure should be greater than the minimum principal stress to form hydraulic cracks in the floor. If the hydraulic cracks extend to the surface of the floor, water inrush occurs [13]. The relationship between the damage variable and the permeability coefficient was established, and then the dangerous area of the floor water inrush was determined [14]. The splitting effect of water pressure on the floor water-resistant layer was analyzed, and the length formula of the split zone at both ends of the crack under the water pressure was given [15].
Karst collapse columns are distributed in 45 coal mining areas in 20 coal fields in China [16]. The water inrush under such geological conditions was caused by the fracturing of the secondary stress field formed by the excavation and the static and dynamic hydraulic pressure in the collapse column. The coupling model of seepage-damage-fracture of karst water inrush was established, and the interaction between seepage and strength damage of rock mass under high osmotic pressure was revealed [17].

In tunnel engineering, a large amount of water inrush has occurred under high water pressure with hydraulic fracturing effect (Table 1 [18]). Regarding the mechanical mechanism of the hydraulic fracturing effect of tunnel water inrush, the critical water pressure of hydraulic fracturing caused by hydrostatic pressure was studied [18, 19]. The hydraulic fracturing effect of tunnel water inrush is divided into two failure modes: tension-shear failure and compression-shear failure. The criteria for these two modes of water inrush were established, respectively [20, 21]. The critical water pressure for tensile-shear failure of cracks was much greater than that for compression-shear failure, so the rock was more prone to compression-shear failure [22, 23]. When the tunnel was drilled and blasted, the critical water pressure when the hydraulic crack occurred in compression and shear failure was calculated [24]. The evolution equation of the fracture damage of the corrosion-damaged rock mass was established, and then the hydration-hydraulic damage equation was constructed [25]. The minimum safe thickness of the rock wall in the case of hydraulic fracturing of water inrush occurs in the tunnel under the disturbance of blasting excavation [24, 26]. However, these studies failed to consider the pore water pressure gradient effect of hydraulic fracturing, so the established theory has certain limitations.

Based on the experimental law of true triaxial hydraulic fracturing, this paper established a mechanical calculation model for high-pressure water inrush during tunnel excavation by blasting. Then, the established mechanical model was solved. Finally, an example was used to verify the correctness of the theoretical derivation.

2. Mechanical Model

After hydraulic fracturing with red dye water on a true triaxial experimental system, the hydraulic morphology in the rock can be divided into “four zones and three fronts” (Figure 1 [27] and Figure 2 [28]). The four zones are the macrohydraulic fracture zone, the microcrack zone, the osmotic hydraulic zone, and the nonwetting zone. The three fronts are the hydraulic fracture front, the microcrack front, and the water pressure front. The boundary between the macrohydraulic fracture zone and the microcrack zone is called the hydraulic fracture front. The boundary between the microcrack zone at the tip of the hydraulic crack and the osmotic hydraulic zone is called the microcrack front. The junction of the osmotic hydraulic zone and the nonwetting zone is called the water pressure front. The macrohydraulic crack zone and the microcrack zone at the tip of the crack were dyed with red dye water, and the color of the macrohydraulic crack zone was obviously darker than that of the microcrack area. However, the osmotic hydraulic zone was not dyed. It shows that the width of hydraulic cracks in the macrohydraulic fracture zone is larger, and the microcrack zone at the tip of the crack forms cracks with a small width. No cracks were formed in the osmotic hydraulic zone.

The hydraulic fracturing of high-pressure water in the source of water inrush disaster shows macroscopic hydraulic cracks in the surrounding rock. The macrohydraulic fracture zone is formed from the high-pressure water source to the tip of the macrohydraulic fractures. As the high-pressure water gradually flows to the tip of the macrohydraulic fracture and seeps around the macrohydraulic fracture, the water pressure at the tip of the macrohydraulic fracture gradually increases. This reduces the hydraulic gradient in the hydraulic cracks. Since the rock is composed of mineral particles [29], there are pores between the particles [30]. The mineral particles form the skeleton of the rock, and the pores are the channels in the rock that allow fluids to flow in them. High-pressure water seeps from hydraulic cracks into the pores of the surrounding rock, forming pore pressure. In the seepage process, the water pressure attenuates from the hydraulic fracture to the seepage area, forming a pore pressure gradient. An osmotic hydraulic zone is formed around the hydraulic fracture. The stress concentration in front of the hydraulic fracture tip is high, so the mineral particles here are most likely to be damaged. When the pore water pressure and the framework stress exceed the bond strength between the mineral particles, the mineral particles at the tip of the hydraulic fracture are split and the microcrack zone is formed. The energy required for rock failure is the smallest perpendicular to the direction of the minimum principal stress, so the direction of the microcracks is along the direction.

Based on the above analysis, a plane mechanical model of the high-pressure water inrush during tunnel excavation is established, as shown in Figure 3. After excavation, the stress in the surrounding rock is redistributed, and a disturbing stress zone is formed in front of the tunnel face. Under the action of in situ stress, disturbance stress, and hydraulic fracturing, the surrounding rock cracks, forming macroscopic hydraulic fractures. The water in the water inrush source penetrates into the pores around the hydraulic fracture to form a permeable zone. The mineral particles at the tip of the hydraulic fracture are split under the combined action of the pore water pressure gradient and the framework stress, forming a microcrack zone. The mineral particles that make up the rock vary in shape. However, the shape of the mineral particles composing the rock is simplified to an equal diameter circle for the convenience of mechanical analysis. According to the results of the acoustic emission monitoring hydraulic fracturing laboratory experiment [31] and the microseismic monitoring hydraulic fracturing field test [32], it is found that the fracture propagation of rock hydraulic fracturing is dominated by shear failure and composite failure. Therefore, two types of crack, tensile-shear failure and compression-shear failure, are specifically analyzed.

Drilling and blasting are the main method of tunnel excavation. When the tunnel is excavated by drilling and
blasting, the excavation disturbance stress is caused by the explosion stress wave on the surrounding rock. The blasting excavation redistributes the stress in the surrounding rock and disturbs the high-pressure water at the source of the water inrush hazard. The original equilibrium state between high-pressure water and surrounding rock is broken. Hydraulic cracks begin to crack and expand [33] under the action of blasting disturbance stress and hydraulic fracturing. In this paper, a two-dimensional plane calculation model of water inrush from the complete rock mass and the fractured rock mass under the action of an explosion stress wave is established.

The rock mass is subjected to the static load of in situ stress ($\sigma_1$ and $\sigma_3$) and water pressure, as well as the dynamic

| Number | Location         | Bad geology                          | Water source            | Outlet position | Water inrush characteristics                  |
|--------|------------------|--------------------------------------|-------------------------|-----------------|-----------------------------------------------|
| 1      | Bagualing Tunnel | A large cave on the left arch        | Karst water             | Advanced geological exploration                  | Water inflow was 15,000 m$^3$/h                       |
| 2      | Yuanliangshan Tunnel DK354 + 879 | Cave in front                      | High-pressure karst water | Face            | Peak water inrush volume was 3000 m$^3$/h                  |
| 3      | Yuanliangshan Tunnel DK361 + 764 | A karst pipeline on the right side and developed bedding cracks | Karst water head is about 200 m | Karst pipeline | Maximum water inflow was 216 m$^3$/min                      |
| 4      | Bieyancao Tunnel DK406 + 422 | The junction of soluble rock and non-soluble rock | High-pressure karst water | Rock blast hole | The initial water pressure was over 1.0 MPa                |
| 5      | Bieyancao Tunnel DK406 + 680 ~ 710 | Fault zone, a dark river on the right | Karst water             | Right wall      | Peak water inflow was 2100 m$^3$/h                       |
| 6      | Pishuangao Tunnel RK63 + 094~102 | Developed karst                    | Karst water             | Construction joints at the bottom of the tunnel | Gushing                                               |
| 7      | Yesanguan Tunnel DK124 + 602 | Fault fracture zone                  | Karst water             | Face            | Water inflow in the first 30 minutes was 151,000 m$^3$       |
| 8      | Wuzhishan Tunnel K29 + 543 | Fault fracture zone                  | Karst water             | Face            | Peak water inflow was 16,000 m$^3$/d                    |

Figure 1: Typical tunnel water inrush accidents with hydraulic fracturing effect [18].

Figure 2: “Four zones and three fronts” around hydraulic fractures [28].
load disturbance of the explosive stress wave (P wave and SV wave). Therefore, the high-pressure water inrush under the conditions of blasting excavation is induced by the superposition of static and dynamic loads. For complete rock mass (Figure 4), the water pressure in the water source is $p$. It is assumed that the shape of the high-pressure water source is circular. For fractured rock mass (Figure 5), the direction of hydraulic cracks is the $X$-axis direction, and the direction perpendicular to the hydraulic cracks is the $Y$-axis direction. The angle between the hydraulic crack and the direction of the in situ stress $\sigma_1$ is $\alpha$. The shear stress on the crack surface is $\tau$. The normal stress is $\sigma_n$, $\gamma$ is the angle between the incident wave and the $X$-axis. The crack water pressure is $p$.

3. Water Inrush Mechanism Based on Dynamic and Static Superposition Effect

3.1. Water Inrush with Hydraulic Fracturing Effect from Intact Rock Mass. As shown in Figure 4, the rock mass at a certain distance from the high-pressure water source is in a plane strain state, and its stress [34] can be expressed as

$$\sigma_\theta = \sigma_1 + \sigma_3 - 2(\sigma_1 - \sigma_3)\cos 2\theta, \quad (1)$$

$$\sigma_r = 0, \quad (2)$$

where $\sigma_\theta$ and $\sigma_r$ are, respectively, the tangential stress and the radial stress and $\theta$ is the angle between a point around the high-pressure water source and $\sigma_1$.

When $\theta = 0$, the tangential stress $\sigma_\theta$ takes the minimum value, which is $3\sigma_3 - \sigma_1$.

When the water pressure is greater than the sum of the tangential stress and the tensile strength of the rock, the rock cracks. Therefore, the critical water pressure $p_s$ for rock cracking under static load is

$$p_s = 3\sigma_3 - \sigma_1 + \sigma_1, \quad (3)$$

When the tunnel is excavated by blasting, the rock cracking around the water inrush source is subjected to not only the static load of the water pressure and ground stress but also the dynamic load of the blast stress wave. If the disturbing effect of the explosion stress wave on the rock is
$p_r$, the critical water pressure for rock cracking under the action of static and dynamic loads is

$$p = 3\sigma_3 - \sigma_1 + \sigma_p - p_r.$$  

(5)

3.2. Water Inrush with Hydraulic Fracturing Effect from Fractured Rock Mass. The instability propagation of hydraulic cracks during blasting excavation is the result of the superposition of static loads (water pressure and in situ stress) and dynamic loads (explosive stress waves). According to the superposition principle, when multiple loads are applied to a crack in the linear elastic range, the total stress intensity factor at the crack tip is equal to the sum of the stress intensity factors under the individual loads that produce the same crack propagation mode. The stress intensity factor of the crack under the conditions of blasting excavation should be the superposition of the stress intensity factor generated under the combined action of static and dynamic loads, namely,

$$K_e = K_{es} + K_{ed},$$  

(6)

where $K_e$ is the stress intensity factor, $K_{es}$ is the static stress intensity factor, and $K_{ed}$ is the dynamic stress intensity factor.

As shown in Figure 5, if the impact of the explosive stress wave on the cracks is not considered, the static stress state on the surface of the water-bearing crack can be expressed as

$$\sigma_n = -\left(\frac{\sigma_1 + \sigma_3}{2} - \frac{\sigma_1 - \sigma_3}{2} \cos 2 \alpha - p \right),$$  

(7)

$$\tau = -\frac{\sigma_1 - \sigma_3}{2} \sin 2 \alpha.$$

The normal stress $\sigma_n$ of the crack may be tensile stress or compressive stress. If it is tensile stress, I-II tensile-shear composite failure will occur. If it is compressive stress, I-II compression-shear composite failure will occur.

3.2.1. Water Inrush Caused by Tension-Shear Combined Hydraulic Cracks. For I-II tensile-shear composite cracks, the approximate fracture judgment criteria in engineering can be used [35]. The hydraulic crack propagation criterion can be expressed as

$$K_{IC} = K_{I} + K_{II} + K'_{I} + K'_{II},$$  

(8)

where $K_{IC}$ is the stress intensity factor of I-II tensile-shear expansion; $K_{I}$ and $K_{II}$ are the stress intensity factors of type I and type II caused by static load, respectively; and $K'_{I}$ and $K'_{II}$ are the stress intensity factors of type I and type II caused by dynamic load, respectively.

According to fracture mechanics, the stress intensity factors of type I and type II crack tips are, respectively,

$$K_I = \sigma_e \sqrt{\pi a},$$  

(9)

$$K_{II} = \tau_e \sqrt{\pi a},$$  

(10)

where $a$ is the length of the hydraulic crack at the side of the high-pressure water source near the excavation, $\sigma_e$ is the effective normal stress on the surface of the hydraulic crack, and $\tau_e$ is the effective shear stress on the surface of the hydraulic crack.

The rock is permeable. After hydraulic fracturing, there are “four zones and three frontiers” in the rock. There are no cracks in the osmotic hydraulic zone, but there is the pore water pressure. The pore water pressure gradient is formed from the hydraulic crack to the water pressure front in the osmotic hydraulic zone. Pore pressures of different sizes have a splitting effect at the crack tip. The pore water pressure splitting factor $\lambda$ is introduced to express this splitting effect.

Subsequently, the effective normal stress $\sigma_e$ and effective shear stress $\tau_e$ on the crack surface are, respectively,

$$\sigma_e = \sigma_n - \lambda p,$$  

(11)

$$\tau_e = \tau - \lambda p.$$  

(12)

Namely,

$$\sigma_e = \left(\frac{\sigma_1 + \sigma_3}{2} - \frac{\sigma_1 - \sigma_3}{2} \cos 2 \alpha + (\lambda - 1)p \right)\sqrt{\pi a}. \quad (13)$$

For type I cracks under the influence of the pore water pressure gradient, the stress intensity factor at the tip of the hydraulic crack is

$$K_I = \left(\frac{\sigma_1 + \sigma_3}{2} - \frac{\sigma_1 - \sigma_3}{2} \cos 2 \alpha + (\lambda - 1)p \right)\sqrt{\pi a}. \quad (14)$$

For type II cracks, the stress intensity factor at the tip of the hydraulic crack is

$$K_{II} = \left(\frac{\sigma_1 - \sigma_3}{2} \sin 2 \alpha + \lambda p \right)\sqrt{\pi a}. \quad (15)$$

When tunnels are excavated by blasting, the blast stress waves propagating in the rock mass are mainly P waves and SV waves. The type I and type II dynamic stress intensity factors generated by the P wave and SV wave at the tip of a water-bearing crack are analyzed [35]. It is considered that the type II dynamic stress intensity factor generated by the SV wave at the crack tip is larger, so the dynamic stress intensity factor generated by the P wave can be ignored. Therefore, the main analysis is the dynamic stress intensity factor generated by the SV wave incident on the crack surface. Since water can only propagate longitudinal waves and the total energy projected by the rock mass into the water is relatively small, the influence of the water in the crack on the stress wave is not considered.

$\phi^{(i)}(x, y, t)$ and $\psi^{(i)}(x, y, t)$ are the incident wave field; then the incident wave (SV wave) field [21] is
\begin{equation}
\phi^{(i)}(x,y,t) = 0, \tag{16}
\end{equation}

\begin{equation}
\psi^{(i)}(x,y,t) = \psi_0 \exp[-i(\beta(x \cos \gamma + y \sin \gamma) + \omega t)], \tag{17}
\end{equation}

\begin{equation}
\beta = \frac{\omega}{c_i}, \tag{18}
\end{equation}

where $\omega$ is the circular frequency, $c_i$ is the speed of the SV wave, $\beta$ is the wave number, and $\psi_0$ is a constant.

From equations (17) and (18), the peak vibration velocity $v$ of the explosion stress wave SV wave can be obtained as

\begin{equation}
v = \frac{\beta \omega \psi_0}{c_s}, \tag{19}
\end{equation}

The dynamic stress intensity factor generated by the SV wave at the tip of the hydraulic crack [35] is

\begin{equation}
K'_I(t) = \tau_1 \sqrt{\pi a} |K_{I|^2}^{(2)}| \exp[-i\omega(t - \delta _2^{(1)})], \tag{20}
\end{equation}

where $|K_{I|^2}^{(2)}|$ are the dynamic stress intensity factors, $\delta _2^{(1)}$ and $\delta _2^{(2)}$ are the phase angles, and $\mu$ represents the Lame constants.

\begin{equation}
\tau_1 = \mu^2 \psi_0, \tag{21}
\end{equation}

\begin{equation}
K''_I(t) = \tau_1 \sqrt{\pi a} |K_{II|^2}^{(2)}| \exp[-i\omega(t - \delta _2^{(2)})].
\end{equation}

3.2.2. Water Inrush Caused by Compression-Shear Combined Hydraulic Cracks. When the normal stress on the surface of the hydraulic crack is compressive stress, the crack propagation mode is the I-II compression-shear compound type. Based on the maximum circumferential stress theory [36], the circumferential stress $\sigma_\theta$ [24] at $(r, \theta)$ can be expressed as

\begin{equation}
\sigma_\theta = \frac{1}{2\sqrt{2\pi r}} \cos \frac{\theta}{2} \left[3(K_{II} + K_{I}) \sin \theta - (K_I + K'_I)(1 + \cos \theta) \right]. \tag{25}
\end{equation}

The crack propagation proceeds along the section of maximum circumferential stress $\sigma_{\theta,\text{max}}$ and the angle $\theta_0$ between the section and the crack is the propagation angle of the crack tip. Therefore, the equivalent stress intensity factor for hydraulic crack propagation is

\begin{equation}
K_e = \sigma_\theta (r, \theta_0) \sqrt{2\pi r}, \tag{26}
\end{equation}

If the effects of crack thickness and tip curvature radius are neglected, the propagation angle of the compression-shear compound crack is a fixed value [37], which is $\theta = \arctan 2\sqrt{2}$. If $K_I = K'_I = 0$, the equivalent stress intensity factor when the hydraulic crack propagates under the

\begin{equation}
K_e = \sigma_\theta (r, \theta_0) \sqrt{2\pi r}. \tag{26}
\end{equation}

To analyze the maximum impact of the dynamic stress intensity factor generated by the SV wave on the crack growth, $K'_I(t)$ and $K''_I(t)$ take the maximum value. Regardless of the changes of the dynamic stress intensity factor with time and phase angle, equation (20) becomes

\begin{equation}
K'_I = \tau_1 \sqrt{\pi a} |K_{I|^2}^{(2)}|, \tag{22}
\end{equation}

\begin{equation}
K''_I = \tau_1 \sqrt{\pi a} |K_{II|^2}^{(2)}|. \tag{22}
\end{equation}

Substituting formulae (14), (15), and (22) into formula (8), the equivalent stress intensity factor during the growth of the I-II type tension-shear compound hydraulic crack propagation is obtained, namely,

\begin{equation}
K_{IC} = -\sqrt{\pi a} \left[\frac{\sigma_1 + \sigma_3}{2} - \frac{\sigma_1 - \sigma_3}{2} \cos 2\alpha + (2\lambda - 1)p \right. \tag{23}
\end{equation}

\begin{equation}
\left. + \frac{\sigma_1 - \sigma_3}{2} \sin 2\alpha - \tau_1 \left(\left|K_i^2\right| + \left|K_{II}^2\right|\right)\right].
\end{equation}

According to the change law of dynamic stress intensity factors $|K_{I|^2}^{(2)}|$ and $|K_{II|^2}^{(2)}|$ [35], the angle between the incident wave and the crack's long axis is $60^\circ$ when the sum of $|K_{I|^2}^{(2)}|$ and $|K_{II}^2|$ reaches the maximum value. At this angle, the explosive stress wave has the greatest disturbing effect on the water-bearing cracks.

Therefore, the critical water pressure when the surrounding rock undergoes hydraulic fracturing effect of water inrush with combined tensile and shear failure is

\begin{equation}
\rho_c = \frac{1}{1 - 2\lambda} \left[ \frac{K_{IC}}{\sqrt{\pi a}} + \frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2} \sin 2\alpha - \frac{\sigma_1 - \sigma_3}{2} \cos 2\alpha - \tau_1 \left(\left|K_i^2\right| + \left|K_{II}^2\right|\right)\right]. \tag{24}
\end{equation}

The dynamic stress intensity factor generated by the SV wave on the crack growth, $K'_I(t)$ and $K''_I(t)$ take the maximum value. Regardless of the changes of the dynamic stress intensity factor with time and phase angle, equation (20) becomes

\begin{equation}
K'_I = \tau_1 \sqrt{\pi a} |K_{I|^2}^{(2)}|, \tag{22}
\end{equation}

\begin{equation}
K''_I = \tau_1 \sqrt{\pi a} |K_{II|^2}^{(2)}|. \tag{22}
\end{equation}

The static stress intensity factor is still

\begin{equation}
K_{IC} = 2 \sqrt{3} (K_{II} + K_{I}). \tag{27}
\end{equation}

When the normal stress is compressive stress, the hydraulic crack is closed. The hydraulic crack surface is expanded under the action of shearing force. Compressive stress also has frictional force on the hydraulic crack surface to resist the movement of the crack surface. The effective shear stress can be expressed as

\begin{equation}
t_e' = \begin{cases} 0, & |r| < (f\sigma_n + c), \\ |r| - (f\sigma_n + c) - \lambda p, & |r| \geq (f\sigma_n + c), \end{cases} \tag{28}
\end{equation}

where $t_e'$ is the effective shear stress of the crack surface under compression-shear stress, $f$ is the friction coefficient, and $c$ is the cohesive force of the hydraulic crack surface. The effective normal stress is the same as that of the tension-shear composite hydraulic crack, namely,

\begin{equation}
\sigma_e = \left(\frac{\sigma_1 + \sigma_3}{2} - \frac{\sigma_1 - \sigma_3}{2} \cos 2\alpha + (\lambda - 1)p\right). \tag{29}
\end{equation}

The static stress intensity factor is still

\begin{equation}
K_{IC} = 2 \sqrt{3} (K_{II} + K_{I}). \tag{27}
\end{equation}
4. Case Analysis

A typical hydraulic fracturing effect of high-pressure water inrush occurred in the Jinping deep-buried (2848 m) exploration cave. According to the measured data of Huang Runqiu et al. [38], the \( \sigma_1 \) in situ stress was 8.16 MPa and \( \sigma_3 \) was 14.81 MPa. The fracture toughness \( K_{IC} \) value of the mode I crack in marble was 15.2 MN/m\(^{3/2}\). It can be seen from equation (23) that \( K_{IC} \) is a negative value, so the calculation should be \(-15.2\) MN/m\(^{3/2}\). The fracture toughness \( K_{IC} \) of type II crack was 11.2 MN/m\(^{3/2}\), which should be a negative value during calculation. The internal friction angle \( \phi \) on the hydraulic crack surface was 30°, and the hydraulic crack length \( a \) was 1.1 m. The angle between the long axis of the crack and the maximum principal stress was 0°. In addition, the pore water pressure splitting factor was 0.38, and the cohesive force \( c \) was 14.98 MPa. When the incident angle of the blasting stress wave was 60°, the blasting disturbance load \( \tau_1 \) \( (|K_{II}^{(2)}| + |K_{II}^{(2)}|) \) was taken as 4.23 MPa. The angle between the incident wave and the long axis of the hydraulic crack is about 90°, and the blasting disturbance load \( \tau_1 |K_{II}^{(2)}| \) was 1.26 MPa [35].

Substituting the above parameters into equation (24), the critical water pressure of fracturing water inrush when the surrounding rock undergoes tensile-shear composite failure was 10.01 MPa. Substituting these parameters into equation (33), it can be obtained that the critical water pressure of water inrush when the surrounding rock undergoes compression-shear failure was 2.12 MPa. The on-site measurement of the water pressure of the water inrush was 2.08 MPa. Therefore, the hydraulic crack propagation mode of the fracturing water inrush here should be the compression-shear failure type.

5. Conclusion

(1) Based on the experimental law of true triaxial hydraulic fracturing, a mechanical calculation model for high-pressure water inrush during tunnel blasting and excavation was established.

(2) When the pore water pressure, skeleton stress, and blasting disturbance stress at the tip of the hydraulic crack exceed the bond strength of the mineral particles, the mineral particles are split and micro-cracks are formed at the tip of the hydraulic crack.

(3) For fracturing water inrush of fractured rock mass, two types of water inrush were proposed: tension-shear composite type and compression-shear composite type. Considering the pore water pressure fracturing factor, these two types of critical water pressure were calculated.
(4) The calculated critical water pressure formula was used to verify the water inrush in the Jinping deep-buried tunnel. The calculated critical water pressure was similar to the measured water inrush pressure, which proved the correctness of the deduced theory.

Data Availability

The data used to support the study can be obtained from the corresponding author upon request.

Conflicts of Interest

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

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