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TECHNICAL ARTICLE

Prediction of Water Inrush from Coal Seam Floors Based on the Effective Barrier Thickness

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Abstract
Floor water hazards pose an increasingly prominent risk in China as coal mining depths progressively increase. Two general models of complete and structural floor water inrush that consider the coupled effect of mining stress and water pressure were developed to address the problems caused by highly confined aquifers under these complex stress conditions. We developed an integrated floor water inrush model, and the floor rock mass was rezoned based on the deformation, failure characteristics, and water inrush mechanism of water-resistant floor strata under the combined action of confined water pressure and mine pressure. The formation of the coupled solid–fluid confined water uplift zone was studied from the perspective of fracture propagation. A formulation was obtained that describes the confined floor water under the coupled effects of mine pressure, water pressure, and solid–fluid interaction. An inrush risk prediction is proposed that considers the relationship between the confined water pressure and horizontal principal stress in the bottom plate's pressure relief zone.

Keywords Effective water-resistant layer thickness · Coupled solid–fluid · Water inrush prediction · Pressure water guide belt

Introduction

Floor water inrush originating in Ordovician limestone strata is one of the most common forms of coal mine water disasters in China. Floor water inrushes can occur when the underlying confined water breaks through the mine floor due to geological, hydrogeological, mining, or other factors, and enters the roadway or working face in a sudden, slow, or delayed way, resulting in increased mine water inflow or inundation. Increasing mining depths and the coupled effect of mining intensity, ground stress, and other factors, has led to increasingly diverse forms and complex mechanisms of floor water inrush in in China's deep coal mines. Floor water inrush poses a serious problem to coal production and has thus received extensive research attention. Several water inrush criteria and theories have been proposed, including the water inrush coefficient method, "lower three zones", zero damage theory, thin plate theory, water inrush probability index method, vulnerability index, and main control index system (Derakhshannia et al. 2020; Li 1999; Liu 2009; Ostad-Ali-Askari et al. 2020; Vanani et al. 2017; Wang and Liu 1993; Wu et al. 2013; Zhang and Liu 1997).

The mechanism of water inrushes from deep mining floors has received additional attention in recent years as China works to reduce the threat of high-pressure inrush accidents. Xu (2011) investigated deep mining conditions with floor pressures > 5 MPa to address the failure of complex floor structures and pressure-induced water inrush. The formation and influencing factors, water–rock interaction, spatial and temporal distribution, and law of floor water inrush were analyzed using a large amount of water inrush data. Hu and Tian (2010) studied the ground stress control mechanism of water inrush in deep coal seam floors. Zhao et al. (2015) analyzed the characteristics of floor water inrush in the Hanxing mining area and was the first to propose the floor water inrush mechanism in coal seams as a "breakthrough in different periods and zones" from the

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aspect of rock structure, groundwater dynamics, and linear elastic fracture mechanics, and discussed the mechanism of floor water inrush in coal seams in deep mines and high confined water conditions. Bai (2011) proposed the existence of a water-resistant layer or relatively water-resistant layer at the top of the Ordovician strata, demonstrated its formation mechanism, and successfully applied the theory to multiple mining areas. Zhang et al. (2015) revealed the effect of the stress field-seepage field on the floor lag water inrush mechanism using physical simulation tests to monitor the evolution of deep confined water floor fault extension activation and water channel formation processes. Li et al. (2019) pointed out that the high confining pressure at depth causes a non-linear increase of the mining unloading stress of surrounding rock based on the mechanical behavior of floor masonry beam instability disturbances, which increases the strong disturbance failure zone, and also showed that non-linear strong disturbance failure behavior was more prominent. Ma et al. (2018) used fracture mechanics to deduce the initiation criteria of shear, bedding, and vertical fracturing of floor rock mass. Guo et al. (2018) proposed three types of floor water inrush disaster-causing models (floor crack extension, primary channel conduction, and concealed structure sliding shear failure) based on the hydraulics of a complex rock mass with high confined water–rock mass interaction and high ground stress at depth, and provided water inrush criteria. Yin and Hu (2008) studied the natural guidance mechanism of pressure water through indoor test and field measurement, analyzed the structure, ground stress, rock permeability and physical and mechanical characteristics, water pressure affect the rock water resistance factors, pointed out that the smaller the rock water resistance, the greater is the guiding height, the smaller the penetration coefficient, the head pressure loss, summarized the local key layer overall guiding mechanism, shell fracture cracks and hydraulic fracturing cracks in the under compacted zone. Through theoretical analysis, Zhang et al. (2013) thought that the transition rock mass is most prone to deformation and destruction, and obtained a formula to calculate the pressure water guide stress concentration coefficient through the establishment of fracture mechanics model. Pan et al. (2013) divided the pressurized water guide zone into water erosion, original crack, and crack expansion zones. The fracture expansion condition was analyzed using fracture mechanics from ground stress, pressurized water pressure, and fracture inclination. They pointed out that the capacity of pressurized water to fracture a rock mass under the original condition is very limited and the greater the water pressure and crack inclination, the greater the crack expansion advantage. Hu (2015) established a mechanical model of the bottom plate based on the classical theory of linear elastic fracture, introduced the analytical analysis of the mining depth, vertical distance from the coal seam, fault inclination angle, propulsion direction, supporting pressure concentration and water pressure, and reveals the mechanical mechanism of the mining field. Zhang et al. (2021) investigated the characteristics of the underlying slab on the working surface under the condition of comprehensive numerical calculation and field measurement.

In-depth studies have addressed the mechanism of coal seam floor water inrush, floor stress field distribution, mining effects, monitoring, and prediction. A series of preventive and control techniques and theoretical methods of water pressure mining in coal seams have been proposed, which provide good technical support for ensuring safe mining of deep coal seams under pressure. However, given the inherently complex geological conditions involved in deep mining and high ground stress, high ground temperature, high water pressure, and strong mining disturbance characteristics, water inrushes from deep mining floors are very diverse and their mechanism still requires further exploration and study.

Water inrush from coal seam floors is due to the interaction between confined water and floor strata, the water-resistance of relevant aquifuge and aquitard strata, and mine pressure. High mining pressures tend to destroy aquifuge strata within coal seam floors. This paper therefore establishes an inrush prediction criterion for the working face based on the solid–fluid theory of mining rock mass and the effective thickness of the aquifuge. A formulation was obtained that describes the confined floor water under the combined effect of mine pressure, water pressure, and solid–fluid interaction.

Materials and Methods

Generalization of the Floor Water Inrush Mode

The mine geology determines the inrush type, form, and mechanism. Floor water inrush types have been characterized in various ways in the literature (Table 1). However, the existence and formation of water flow channels in coal floor aquifers and floor aquifuges are required for a floor water inrush to occur, regardless of the inrush type classification. The water pressure and the stability and water resistance of the floor strata together determine whether or not a floor inrush can occur. The integrity of the insulating layer structure is a key factor that determines the likelihood of an inrush. We therefore divided floor water inrushes into two basic modes based on the integrity of the floor aquifuge layer: complete and structural floor water inrushes (Fig. 1a, b, respectively). For a structural floor water inrush, the structure is itself a flow channel. An integrated floor water inrush is caused by communication between the failure and confined water uplift zones. The stability of the floor aquifuge is essentially the decisive factor that controls the inrush.

Table 1 Types of floor water inrush

Classification standard	Classification description of water inrush types		
Water inrush quantity Q	Small inrush	30 m^3/h ≤ Q ≤ 60 m^3/h	
	Medium inrush	60 m^3/h < Q ≤ 600 m^3/h	
	Large inrush	600 m^3/h < Q ≤ 1800 m^3/h	
	Extra-large inrush	Q > 1800 m^3/h	
Formation mechanism of water channel	Inrush from complete water-resisting strata	Inrush from thin water-resisting layer	Water conduction in rock pressure failure zone
		Inrush from thick water-resisting layer	Water-resisting layer fails
	Inrush from concealed structures	The activation of hidden fault generates an inrush from airfoil crack propagation	
	Inrush from inherent flow channel	Natural large-scale water-bearing or water-conductive structures that intersect coal seams are natural channels for water inrush	
Structural form of rock mass	Inrush from normal rock strata	Overall failure mode of thin plate	
		Lifting failure mode of thick plate hydraulic fracturing	
	Fault water inrush mode	Fracture-directed inrush	
		Inrush in uplift zone of confined water affected by fractures	
		Inrush from floor failure zone affected by fracture	
		Inrush from floor failure zone and fissure uplift zone affected by fracture	
	Inrush mode of collapse column	Top–bottom water inrush mode	Theoretical model of thin plate
			Theoretical model of shear failure
		Inrush from side wall of collapse column	Inrush from thick wall tube
			Fracturing water inrush
Types of water-conducting channels	Floor crack expansion	Natural joint fluid–solid coupling extended inrush	
	Primary channel conduction	Cut through the coal seam water channel mining shear sliding water inrush	
	Sliding shear type of concealed structure	Inrush of mining-induced sliding shear type in concealed structure	
Structure of water-resisting layer of floor	Inrush mode of complete floor	Water barrier thickness and lithology combination determine its comprehensive water barrier capacity	
	Inrush mode of fractured structure	Fracture structure weakens the integrity of the water barrier and reduces its effective thickness	
Inrush features	Burst type	The water burst reaches the peak value immediately, and the impact force is consistent with the water pressure, then it stabilizes or decreases gradually	
	Jump type	The sudden water quantity jumps up, the water quantity reaches the maximum value in a short time, then gradually stabilizes; the decreasing trend is not obvious	
	Buffer type	It takes a long time to stabilize the water volume from small to large, up to 1–2 years	
	Lag type	Inrush occurred in the working face for several days, months, or even years, and water quantity was uncertain	
Water inrush location	Inrush in mining space	Occurs mostly near coal wall of floor stope	
	Inrush in tunneling space	Most of the inrush in excavation exposed structure	
	Inrush in goaf	Time lag, lag time varies	

Four-Zone Division

The destruction of a floor includes the movement, deformation, and fracture of the floor rock mass after mining and the formation of a connected water flow channel. Without such destruction, the floor rock mass only undergoes small stress changes or movement after mining and does not allow cracks to connect, thus preventing a water inrush. According to the "lower three zones" theory (Li 1999), a coal seam floor can be divided into a: mine water conductive failure zone, water resistance zone, and confined water conductive zone.

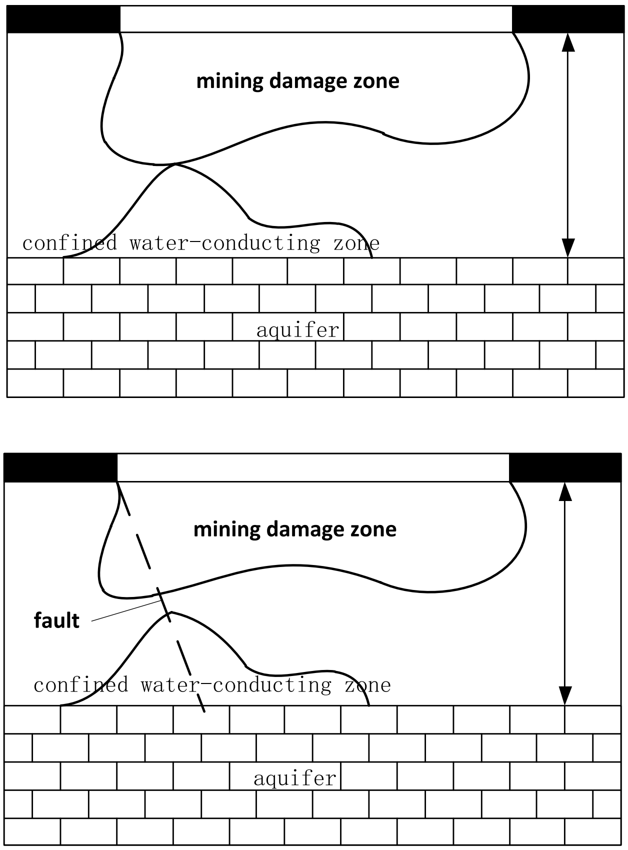


Fig. 1 Generalized floor water inrush model. **a** Complete floor water inrush. **b** Structural floor water inrush

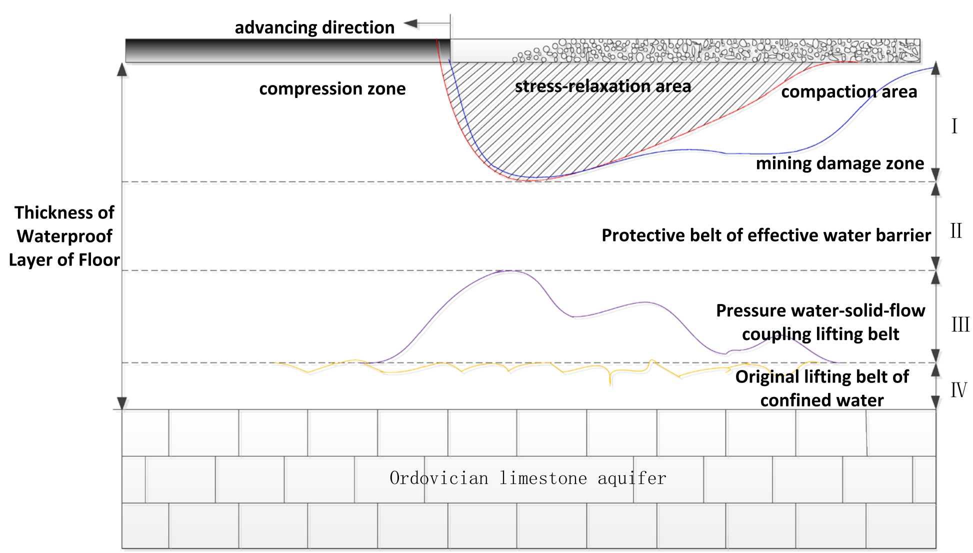
In this paper, the floor rock mass between the coal seam and aquifer was redivided into four zones according to its failure characteristics, from top to bottom: (I) mining failure zone; (II) effective water barrier protection zone; (III) coupled solid–fluid confined water uplift zone; and (IV) confined water original uplift zone. These correspond to the mining failure depth (h_1), effective water barrier thickness (h_2), coupled solid–fluid uplift zone height (h_3), and original uplift zone height (h_4). Zone I is a failure zone formed by the rock mass near the coal seam floor that has been affected by mining pressure. Zone II is an effective protective zone of the aquifuge. The floor rock mass in this zone undergoes little change before and after mining, and only moves vertically without any destructive influence. Zone III is the confined water lifting zone under the coupled effect of confined water and stress-solid flow, which can be referred to as the coupled confined water–solid flow lifting zone. Zone IV is the original confined water uplift zone, which refers to the natural development height of the confined water without the influence of mining. This is all shown in Fig. 2.

Results and Discussion

Formation Mechanism and Height Determination of the Coupled Solid–Fluid Lift Belt for Confined Water

The water–solid-flow lifting zone dictates the height of the confined water that continues to rise along the original fracture of the floor due to the combined effect of mining and water pressure. Formation of a coupled confined water–solid–fluid uplift zone requires that the bottom strata be fractured. The formation of this uplift zone is herein discussed using fracture mechanics and rock pressure control theories and considering the influence of confined water pressure on the stress field at the crack tip (Zhang 2010). A single fractured rock mass is provided as an example (Fig. 3). The fracture length, 2a, is subjected to a bidirectional load, σ_1 and σ_3 are the maximum and minimum principal stresses,

Fig. 2 Division of floor coal seam floor zones



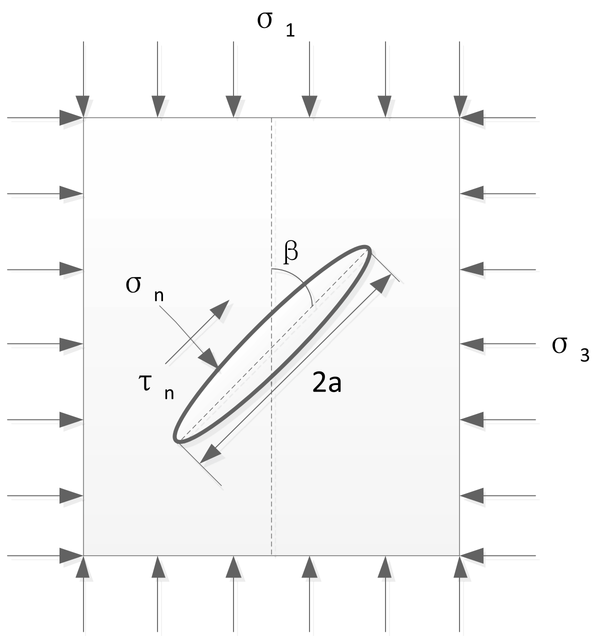


Fig. 3 Stress diagram of a single fractured rock mass

respectively, and β is the angle between the fracture and the σ_1 direction. Because the fracture is under compression, it is affected by both the positive stress σ_n of the vertical surface, and by the shear stress τ_n parallel to the surface:

$$\sigma_n = \frac{\sigma_1 + \sigma_3}{2} - \frac{\sigma_1 - \sigma_3}{2} \cos 2\beta, \tag{1}$$

$$\tau_n = \frac{\sigma_1 - \sigma_3}{2} \sin 2\beta. \tag{2}$$

According to fracture mechanics theory, the simple criterion of crack compound fracture under compression is:

$$\lambda_{12} K_{\mathrm{I}} + K_{\mathrm{II}} = K_{\mathrm{I}c}, \tag{3}$$

where λ_{12} is the compression shear coefficient, K_{Ic} is the fracture toughness under compression that can be obtained from a standard test, and K_{I} and K_{II} are the type-I and type-II stress intensity factors at the crack tip, respectively. Among them:

$$K_{\mathrm{I}} = -\sigma \sqrt{\pi a}, \tag{4}$$

$$K_{\mathrm{II}} = -\tau \sqrt{\pi a}. \tag{5}$$

where σ is the effective positive stress, τ is effective shear stress, and a is the half crack length. The negative sign in Eq. (4) indicates that the type-I stress intensity factor at the crack tip is negative when the crack is subjected to compressive stress. When the water pressure of confined water is considered, the hydrostatic pressure effect reduces the positive stress on the fracture surface; thus the effective positive stress on the fracture surface can be expressed as:

$$\sigma = \sigma_n - p, \tag{6}$$

where p is water pressure. Substituting Eq. (1) into Eq. (6) yields:

$$\begin{aligned} \sigma &= \frac{1}{2}\left[\left(\sigma_1 + \sigma_3\right) - \left(\sigma_1 - \sigma_3\right)\cos 2\beta\right] - p \\ &= \left[\sigma_3 + \left(\sigma_1 - \sigma_3\right)\sin^2 2\beta\right] - p. \end{aligned} \tag{7}$$

Hydrostatic pressure plays a major role in the formation and expansion of cracks due to the confined water in the upward uplift process. Equation (7) can be replaced by Eq. (4) to obtain:

$$K_{\mathrm{I}} = \left\{p - \left[\sigma_3 + \left(\sigma_1 - \sigma_3\right)\sin^2 2\beta\right]\right\}\sqrt{\pi a}. \tag{8}$$

Equation (8) shows that the effective normal stress on the crack surface is zero when the hydrostatic pressure is equal to the normal stress on the crack surface. Accordingly, $K_{\mathrm{I}}=0$ and the crack is in a relatively stable state. If the hydrostatic pressure further increases due to a transfer of mine pressure to the deep bottom plate, the effective normal stress on the crack surface will decrease below zero. At this time, the crack surface is in the tensile stress state ($K_{\mathrm{I}}>0$). With increasing water pressure, the rock fractures when the fracture toughness reaches K_{Ic} and the confined water rises up along the newly expanded crack. The fracture toughness can be obtained by substituting Eqs. (5) and (8) into Eq. (3) to consider the shear stress on the fracture surface.

$$\lambda_{12}\left\{p - \left[\sigma_3 + \left(\sigma_1 - \sigma_3\right)\sin^2 2\beta\right]\right\}\sqrt{\pi a} + \frac{\sigma_1 - \sigma_3}{2}\sin 2\beta\sqrt{\pi a} = K_{\mathrm{I}c}. \tag{9}$$

After collation:

$$2\lambda_{12} p + \sigma_1\left(\sin 2\beta - 2\sin^2\beta\right) + \sigma_3\left(2\sin^2\beta - \sin\beta - 2\right) = \frac{K_{\mathrm{I}c}}{\sqrt{\pi a}}. \tag{10}$$

This can be more simply expressed as:

$$\begin{aligned} &Ap + B\sigma_1 + C\sigma_3 = K_{\mathrm{I}c} \\ &\text{where}: A = 2\lambda_{12}\sqrt{\pi a};\ B = \left(\sin 2\beta - 2\sin^2\beta\right)\sqrt{\pi a};\ C = \left(2\sin^2\beta - \sin\beta - 2\right)\sqrt{\pi a}. \end{aligned} \tag{11}$$

Mine pressure control theory shows that the abutment pressure on a coal body decreases exponentially with depth and the peak stress in the bottom rock changes according to Song (1998):

$$\sigma_Z = K_{\max}\gamma_R h e^{-0.0167Z}, \tag{12}$$

where $K_{\max}$ is the maximum concentration factor of mine pressure, γ_R is the average bulk density of the overlying strata, (kg/cm^3), h is mining depth (m), and Z is the rock depth under the coal seam floor (m). The depth, Z, can be obtained by substituting $\sigma_z = \sigma_1$ into Eq. (11), which is the depth corresponding to the critical stress state, i.e. the depth of the bottom plate where the solid–fluid begins to combine. The confined water begins to rise along the original fracture and the newly extended fracture under the coupled effect of mine pressure and confined water seepage pressure, forming the uplift zone.

$$Z = 59.88 \ln \frac{BK_{\max}\gamma_R h}{\sqrt{\pi a}\left(Ap + C\sigma_3\right) - K_{Ic}}. \tag{13}$$

Establishment of the Effective Waterproof-Layer Thickness Criterion

The test results of the total stress–strain rock permeability (Fig. 4) show that the peak rock permeability generally occurs during the stress softening stage after rock failure (section DE in Fig. 4). The propagation and coalescence of axial rock fractures is a necessary condition for the rapid increase (i.e. jump) in permeability. The relationship between the stress state of the rock and water pressure after fracture propagation and coalescence explains the abrupt permeability jump. The necessary and sufficient conditions of the permeability jump in the rock seepage experiment are applied to the bottom plate water inrush to establish the relationship between the bottom plate water pressure and stress in the bottom plate pressure relief zone. The relationship between the confined water pressure and principal stress in the pressure relief zone is derived using the single fracture propagation mechanical model, as shown in Fig. 5 (Zhang and Pang (2010)). In the figure, σ_1, σ_2, and σ_3 are the principal stresses of the micro-unit along the coordinate axes in the bottom rock mass, σ_x is the normal expansion force of the fissure water along the fissure surface, and τ_x is the tangential force of the water flow. The above model is separated along the fracture surface and the mechanical effect of water is regarded as the model boundary condition. The tetrahedral stress state is shown in Fig. 6 according to elastic–plastic mechanics theory.

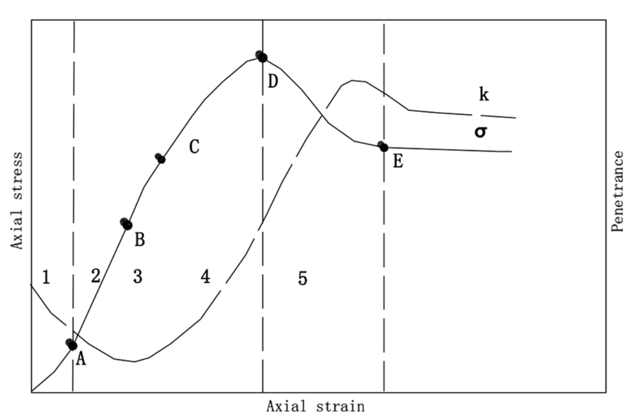


Fig. 4 Complete stress–strain permeability test diagram

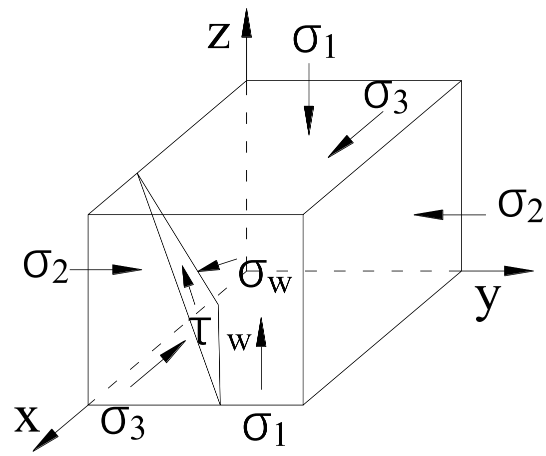


Fig. 5 Mechanical model of single fracture propagation

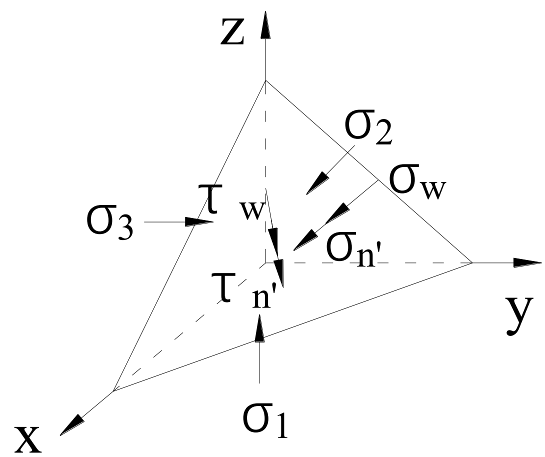


Fig. 6 Stress state of fracture cutting tetrahedron

When the seepage effect of confined water is ignored, the force of the separator on the inclined plane of the fracture is given as:

$$R_n = \sigma_1 l^2 + \sigma_2 m^2 + \sigma_3 n^2$$
$$S_n = \left[l^2 m^2 (\sigma_1 - \sigma_2)^2 + m^2 n^2 (\sigma_2 - \sigma_3)^2 + n^2 l^2 (\sigma_3 - \sigma_1)^2\right]^{1/2}. \quad (14)$$

When considering the seepage effect of confined water, σ_x, and τ_x, the force on the inclined plane is:

$$\sigma_x + R_{Cn} = \sigma_1 l^2 + \sigma_2 m^2 + \sigma_3 n^2$$
$$\tau_x + S_{Cn} = \left[l^2 m^2 (\sigma_1 - \sigma_2)^2 + m^2 n^2 (\sigma_2 - \sigma_3)^2 + n^2 l^2 (\sigma_3 - \sigma_1)^2\right]^{1/2}, \quad (15)$$

where l, m, and n are the direction cosine of the inclined plane and z-, x-, and y-axes, respectively. R_{Cn},S_{Cn} are the forces of the separated part on the inclined plane where there is confined water seepage.

The above analysis shows that a floor water inrush channel is necessary for a sudden floor permeability change. The relationship between the stress state in the extended fractures in the new water inrush channel and confined water pressure is also a sufficient condition for a sudden permeability increase, and for the occurrence of water inrush. For the fracture model, the normal expansive force of water and the tangential force of seepage must exceed the internal force of the fracture surface. Griffith strength theory states that crack propagation is mainly caused by normal tensile stress (Zhang 2020). The tangential force of water and its physical and chemical effects are very limited, which means that the hydrostatic pressure of confined water plays a major role in crack expansion in the actual water inrush process. The sufficient stress and seepage field conditions that should thus be met when the rock permeability jump occurs are:

$$\sigma_x > \sigma_1 l^2 + \sigma_2 m^2 + \sigma_3 n^2. \quad (16)$$

Uniaxial compression test results show that for cracked specimens, crack propagation occurs when the angle between the crack and axial compressive stress direction exceeds 60°; otherwise the direction of the failure surface does not extend along the original crack direction. For safety purposes, we take the angle β between the direction of the penetrating fracture and maximum principal stress and the angle between the intermediate stress and minimum principal stress as 45°, i.e. Equation (16) sets $l=0$, $m=\sqrt{2}/2$, $n=\sqrt{2}/2$, and is simplified to:

$$\sigma_x > \frac{\sigma_2 + \sigma_3}{2}. \quad (17)$$

The relationship between the confined water pressure and horizontal principal stress in the unloading area is therefore satisfied when:

$$P_w > \frac{\sigma_2 + \sigma_3}{2}, \quad (18)$$

where σ_2 and σ_3 are the principal stresses of the floor after unloading, i.e. the principal horizontal stresses of the goaf floor and P_w is the confined water pressure.

A floor water inrush requires that the effective thickness of the aquifuge strata be eliminated by the development, expansion, and penetration of cracks in the mining failure zone of the floor rock mass and coupled solid–fluid uplift zone. Since the relationship between the confined water pressure in the penetrating area and pressure in the unloading area determines the crack opening/closing state in that area, the effective barrier thickness criteria for predicting a floor water inrush is determined by:

1. If the mining failure zone is not connected with the confined water lift zone (i.e. the coupled solid–fluid and original lift zones), there is an effective water barrier thickness of: $h_2 > 0$, namely $M - (h_1 + h_3 + h_4) > 0$, where M is the thickness of the bottom waterproof layer, which implies no water inrush.
2. If the mining failure zone and confined water lifting zone are connected, there is no effective thickness of the insulating layer, but the confined water pressure in the connection area is less than the horizontal principal stress in the floor pressure relief area: $h_2 < 0$, namely $M - (h_1 + h_3 + h_4) < 0$ and $P_w < (\sigma_2 + \sigma_3)/2$, which implies no water inrush.
3. If the mining failure and confined water lifting zones are connected, the insulating layer has no effective thickness, but the confined water pressure in the connection area exceeds the horizontal principal stress in the floor pressure relief area: $h_2 < 0$, namely $M - (h_1 + h_3 + h_4) < 0$ and $P_w > (\sigma_2 + \sigma_3)/2$, which suggests that a water inrush is likely.

Conclusions

Two basic generalization models of complete and structural floor water inrush are proposed. The integrated floor water inrush model allowed the deformation, failure characteristics, and water inrush mechanism of the floor water-resisting strata to be studied under the combined action of confined water pressure and mine pressure during coal mining. The formation mechanism of the joint confined water–solid-flow uplift zone was studied from the perspective of the crack propagation mechanism, and a formula to calculate the floor confined water was derived from the combined effect of rock pressure and water pressure-solid flow. A water inrush risk prediction criterion was proposed based on solid–fluid coupling theory and the relationship between confined water pressure and horizontal principal stress in the bottom plate's pressure relief zone.

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