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TECHNICAL ARTICLE

# Water-Isolating Capacity of an Inclined Coal Seam Floor Based on the Theory of Water-Resistant Key Strata

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**Abstract** A model of an inclined coal seam floor with linearly increasing water pressure was developed based on theories of ground pressure and key strata. The stability metrics of the water-resistant key strata in the inclined coal seam was deduced using Mohr–Coulomb yield criterion. Five principle factors were selected: the distance that the workface had advanced, the tilted length of workface, the thickness and pitch of the water- resistant key strata, and the elasticity modulus. A sensitivity analysis was then conducted using an orthogonal design. The thickness of the water-resistant key strata was the most important factor, with a 44.8% ranking, followed by the distance that the workface had advanced at 34.4%. The influence of the elasticity modulus, pitch, and tilted length of the workface, were 9.3, 5.8, and 5.7%, respectively. The maximum water pressure possibly tolerated by the inclined aquiclude were found to rise with the increasing load of the caved overburden, and decrease with the increasing workface initial or periodic weighting distance, workface length, and pitch of the water-resistant key strata. A parabolic relationship exists between the maximum allowable water pressure and thickness of the key aquiclude. Water-resistant key strata located in the lower part of the confining layer offers better protection from floor water inrush. These findings provide an important theoretical basis to determine the potential of water inrush from an inclined coal seam when mining above confined aquifers.

**Keywords** Water inrush · Prediction model · Orthogonal design · Sensitivity analysis · Geologic setting · Mining operation

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## Introduction

The most serious environmental geological problems induced by human activities include depletion of water resources, groundwater contamination, and geological hazards (Abdelghani et al. 2015; Chaulya 2003; Wu et al. 2011). China's water resources are generally inadequate and inefficiently distributed. Most coal-producing regions in this country are in water-deficient areas. Over 6.1 billion $m^3$ of coal mine drainage are discharged annually in China, which causes serious environmental pollution and represents a waste of available resources (Feng et al. 2014; James and Dave 2015). Enhanced water management and use of mine water (Wang et al. 2015; Wu et al. 2015), including groundwater resources, and preventing water inrush from mines (Wu et al. 2014), can relieve China's water shortage and promote environmental protection.

China is rich in coal resources, but the complexity of its hydrogeological conditions contribute to mine disasters. Increasing mining depth and intensity causes the water and ground pressure on the floor of the mines to increase as the geological structure becomes more complex, and serious water inrush commonly occurs (Han et al. 2009; Miao et al. 2004; Wang and Park 2003; Wu et al. 2004; Zhang 2005). Floor water inrush has caused economic losses and casualties, and serious pollution of groundwater resources and the environment. Therefore, strengthening water resources management, promoting effective use of groundwater resources, and curbing the occurrence of mine water disasters are major issues.

Substantial research has been conducted to investigate coal seam floor water inrush mechanisms to predict and prevent their occurrence (Li et al. 2015; Liang et al. 2015; Meng et al. 2012; Wu and Zhou 2008, 2013; Xu et al. 2012; Yang et al. 2016; Yin and Zhang 2005; Yu et al. 2016). Li (1999) divided the seam floor into three zones: the fractured zone, the intact strata zone, and the zone in which water is rising from the confined aquifer; he concluded that the occurrence of floor water inrush events depends on the intact strata and its water-isolating capacity after mining.

Zhang (2005) suggested that the remaining intact rock layers can be simplified as a four-sided fixed isotropic plate model with a uniform distribution load, and addressed the shear and tensile strength of the remaining intact rock using the Tresca yield criterion and elastic plastic mechanics theory; he also derived a formula for calculating the ultimate water pressure that the floor strata could tolerate. Qian et al. (2003) suggested that a hard rock stratum with a certain thickness and high strength in the remaining intact rock could be used as key floor strata, and studied the limiting step of the strata using thin plate strength theory. Miao et al. (2007, 2008) simplified the water-resistant key strata into a fixed composite rock beam model with a uniform distribution load and analyzed the strength characteristics and its water-isolating capacity.

The hydrogeological conditions of coal mines are complex and coal seams vary. Many inclined coal seams exist, in which a hydraulic gradient exists along the slope direction of the coal seam floor (Sun and Wang 2014; Sun et al. 2011). Most research on water inrush through a mine floor is based on horizontal and near-horizontal coal seams, without considering the influence of the dip of the coal seam on rock strength, broken features, and seepage characteristics of the floor strata (Miao et al. 2007, 2008; Qian et al. 2003; Zhang 2005). If research based on the horizontal and near-horizontal seams are applied to predict water inrush from an inclined coal seam floor, serious errors can occur, resulting in safety hazards.

To predict water inrush through an inclined coal seam floor, the present study established a water-resistant key strata model with linearly increasing water pressure based on theories of ground pressure and key strata. Using the Mohr–Coulomb yield criterion, stability metrics for the key aquiclude were developed for the inclined coal seam floor. The factors influencing the caved overburden load, the weighting distance of stope, the size parameters of water-resistant key strata and its pitch, thickness, location, elasticity modulus, cohesive strength, and internal friction angle on the water-isolating capacity of the key aquiclude were analyzed.

## Water-Resistant Key Strata Model for an Inclined Coal Seam Floor

### Model

Before mining, the top interface of a confined aquifer beneath a coal seam floor is relatively stable (Fig. 1a). As the workface advances, stress concentration and reduction zones occur, leading to the deformation and failure of the

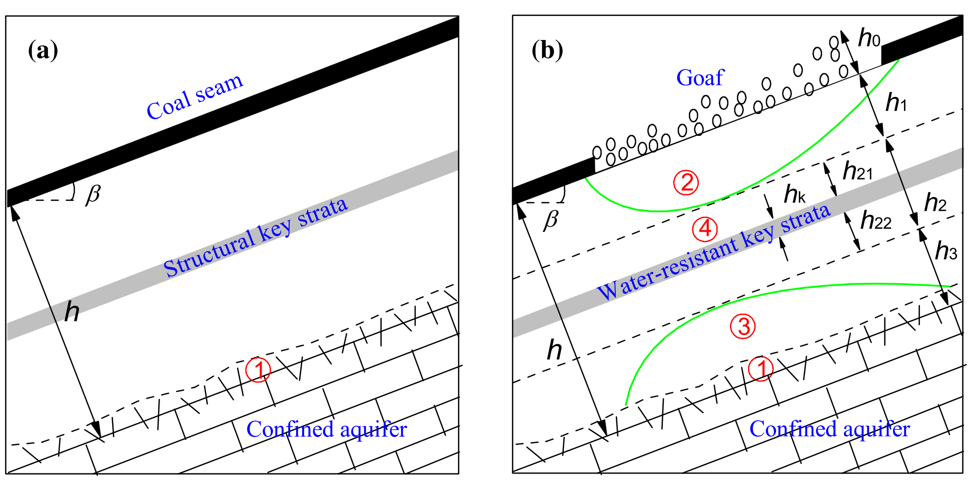


**Fig. 1** Zones of floor failure along the slope direction of a workface floor above a confined aquifer. Zone ① is the original zone of water rising from the confined aquifer, zone ② is the water-conducting fractured zone, zone ③ is the zone of water rising from the confined aquifer as mining progresses, and zone ④ is the confining layer or aquitard, which is the location of the structural key strata that can serve as water-resistant key strata: **a** original water levels in a confined aquifer; **b** water levels in a confined aquifer as mining progresses

surrounding rock mass, including the formation of water-conducting fractures in the coal seam floor. Simultaneously, the confined water in the aquifer can rise in the hydraulic fractures when the stress of the floor strata decreases due to the combined forces of mining and water pressure, which can create a zone of rising water in the aquifer (Fig. 1b). When the rising water in the confined aquifer reaches the water-conducting fractured zone, water inrush from the coal seam floor may occur. An intact aquitard within the floor strata may prevent a water inrush (Fig. 1b), but as the workface advances and the goaf expands, the condition of the mine floor strata can worsen. The forces of mining and water pressure can destroy the confining layer and induce or intensify an outburst of confined water. Given these factors, the occurrence of water inrush through the coal seam floor depends on the stability of the strata in the confining layer.

Based on the key strata theory (Qian et al. 2003), Miao et al. (2007, 2008) suggested that regardless of whether the confined aquifer is located above or below the structural key strata, the structural key strata can have a water-resistant function as long as it remains intact. Any unfractured stratum in the confining layer below the inclined coal seam that has sufficient thickness and strength can be used as the structural key strata. If this structural key strata remain intact after mining, then it can serve as the water-resistant key strata and can prevent water inrush from a confined aquifer (Fan and Zhang 2015; Kong et al. 2007). Thus, determining the existence of structural key strata in the confining layer, and their structural strength, stability, and seepage characteristics, is necessary to prevent and control water disasters in coal mines.

With multi-drilling geological data and rock mechanics testing of an inclined coal seam floor, the thickness, strength, location of each of the coal seam floor strata, including the water pressure distribution of the confined aquifer(s) can be determined. Furthermore, the lithology, thickness, density, strength (compressive strength, tensile strength, shear strength), and other parameters of the structural key strata of the floor can be determined under the site-specific geological conditions. The lithology, thickness, density, strength, location, and other parameters of the structural key strata generally vary. They may be some type of sandstone, shale, or mudstone but must be hard, with a compressive strength generally higher than 20 MPa, though the specific situation is determined by the drilling data. In other words, if the structural key strata are thicker and more complete, the carrying capacity is greater, and the corresponding water-isolating capacity is stronger.

To analyze the stability and water-isolating capacity of the confining layer, as well as to predict water inrush from an inclined coal seam floor, the structural key strata in the confining layer can be extracted from Fig. 1. Furthermore, they can form a water-resistant key strata model, as shown in Fig. 2, where $h_0$ is the height of the caved overburden and $\gamma_0$ is its average bulk density; $h_1$ is the depth of the water-conducting fractured zone in the inclined coal seam floor and $\gamma_1$ is its average bulk density; $h_2$ is the thickness of the confining layer, and $\gamma_2$ is its average bulk density; $h_3$ is the height of the zone in which water is rising from the confined aquifer as mining progresses, and $\gamma_3$ is its bulk density; $h_k$ is the thickness of the water-resistant key strata and $E_k$ is its average modulus of elasticity, and $\gamma_k$ is its bulk density, $\mu_k$ is its Poisson's ratio, and $\beta$ is its dip angle; $h_{21}$ and $h_{22}$ are the thickness of any part of the confining layer lying above and below key strata, respectively, that satisfies $h_{21}+h_k+h_{22}=h_2$, as shown in Fig. 1b.

## Load Distribution

Based on the ground pressure and strata control theory (Qian and Shi 2003), inclined water-resistant key strata

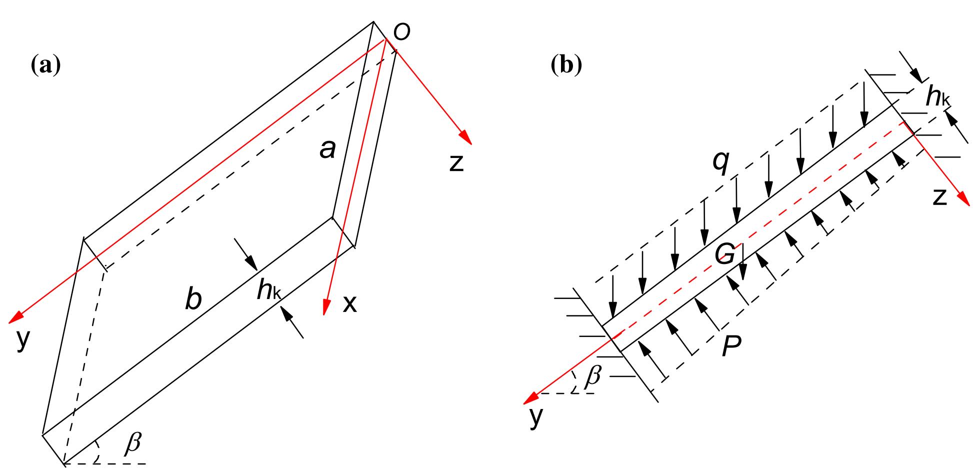


**Fig. 2** The water-resistant key strata model (**a**) and its load distribution (**b**) for an inclined coal seam floor (after Sun and Wang 2014)

can be treated as a clamped inclined rectangular thick plate (Fig. 2a), where $x$ is the workface's advancing direction with the width of $a$; $y$ is the tilted direction along the workface, with the length of $b$; and $z$ is the downward direction perpendicular to the water-resistant key strata. The vertical downward load acting on the surface of the key strata includes the caved overburden load $q_0=\gamma_0 h_0$, the strata load $\gamma_1 h_1$ of the water-conducting fractured zone, and the strata load $\gamma_2 h_{21}$ of the confining layer lying above the key strata. The total vertical load is $q=q_0+\gamma_1 h_1+\gamma_2(h_2-h_k-h_{22}) = \gamma_0 h_0+\gamma_1 h_1+\gamma_2 h_{21}$, and the body force of the key strata is $G=\gamma_k h_k$, as shown in Fig. 2b.

A hydraulic gradient exists along the slope of an inclined coal seam floor, but the water load acting perpendicular to the lower surface of the water-resistant strata cannot be easily seen as equally distributed water pressure. To simplify the problem, we assumed that the water load $P$ acting on the lower surface of the water-resistant key strata increases linearly along the tilted direction of the coal seam floor (Fig. 2b), which is proportional to the vertical height of the workface and can be expressed as follows:

$$P = \frac{\rho g \Delta H}{b} y + P_o = \rho g y \sin\beta + P_o, \tag{1}$$

where $P_o$ is the water pressure of the floor confined aquifer at the upper end of the workface, $\Delta H$ is the vertical height of the workface, $\rho$ is the water density of the floor confined aquifer, and $g$ is the gravity acceleration.

## Stability Metrics for Inclined Water-resistant Key Strata

### Deflection Function

The load distribution characteristics of the water-resistant key strata indicate that the lateral loads acting on it are kept constant in the $x$ direction and increase linearly in the $y$ direction, which satisfies Eq. (1). The deflection function that satisfies the boundary conditions of the four-sided clamped plate is:

$$w = Ay\sin^2\left(\frac{\pi x}{a}\right)\sin^2\left(\frac{\pi y}{b}\right), \tag{2}$$

where $A$ is the coefficient of deflection function $w$. According to the principle of minimum potential energy (Timoshenko and Woinowsky-Krieger 1959; Xu 2006), the deflection function for the inclined water-resistant key strata can be determined by:

$$w = \frac{b\left\{\left[\gamma_0 h_0+\gamma_1 h_1+\gamma_2 h_{21}+\gamma_k h_k\right]\cos\beta - P_0 - \left(\frac{2}{3}-\frac{1}{\pi^2}\right)\rho g b\sin\beta\right\} y\sin^2\left(\frac{\pi x}{a}\right)\sin^2\left(\frac{\pi y}{b}\right)}{\left(\frac{E_k h_k^3}{6(1-\mu_k^2)}\left[\left(\frac{\pi}{a}\right)^4 b^2\left(1-\frac{15}{8\pi^2}\right)+\left(\frac{\pi}{b}\right)^2\left(\pi^2+\frac{15}{8}\right)+\left(\frac{\pi}{a}\right)^2\left(\frac{2}{3}\pi^2-\frac{1}{4}\right)\right]\right)} \tag{3}$$

### Criterion

The stresses for the water-resistant key strata can be obtained by the relationship between the stress and deflection functions of an elastic rectangular thin plate (Timoshenko and Woinowsky-Krieger 1959; Xu 2006), as follows:

$$\left.\begin{aligned}
\sigma_x &= \frac{E_k z A}{1-\mu_k^2}\left\{\frac{2\pi^2}{a^2} y\cos\left(\frac{2\pi x}{a}\right)\sin^2\left(\frac{\pi y}{b}\right)+\mu_k\left[\frac{2\pi}{b}\sin^2\left(\frac{\pi x}{a}\right)\sin\left(\frac{2\pi y}{b}\right)+\frac{2\pi^2}{b^2} y\sin^2\left(\frac{\pi x}{a}\right)\cos\left(\frac{2\pi y}{b}\right)\right]\right\}\\
\sigma_y &= \frac{E_k z A}{1-\mu_k^2}\left[\frac{2\pi}{b}\sin^2\left(\frac{\pi x}{a}\right)\sin\left(\frac{2\pi y}{b}\right)+\frac{2\pi^2}{b^2} y\sin^2\left(\frac{\pi x}{a}\right)\cos\left(\frac{2\pi y}{b}\right)+\mu_k\frac{2\pi^2}{a^2} y\cos\left(\frac{2\pi x}{a}\right)\sin^2\left(\frac{\pi y}{b}\right)\right]\\
\tau_{xy} &= \frac{E_k z A}{1+\mu_k}\left[\frac{\pi}{a}\sin\left(\frac{2\pi x}{a}\right)\sin^2\left(\frac{\pi y}{b}\right)+\frac{\pi^2}{ab} y\sin\left(\frac{2\pi x}{a}\right)\sin\left(\frac{2\pi y}{b}\right)\right]
\end{aligned}\right\} \tag{4}$$

where $\sigma_x$, $\sigma_y$, and $\tau_{xy}$ are stress components, and $0 \leq x \leq a$, $0 \leq y \leq b$, $-h_k/2 \leq z \leq h_k/2$. The principal stress at any point on the inclined strata can be obtained from the relationship between stress components and principal stresses:

$$\sigma_1, \sigma_3 = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \left(\tau_{xy}\right)^2} = B_1 \pm B_2, \tag{5}$$

where:

$$\left.\begin{aligned} B_1 &= \frac{E_k z A}{1-\mu_k}\left[\frac{\pi^2}{a^2} y\cos(\frac{2\pi x}{a})\sin^2(\frac{\pi y}{b}) + \frac{\pi}{b}\sin^2(\frac{\pi x}{a})\sin(\frac{2\pi y}{b}) + \frac{\pi^2}{b^2} y\sin^2(\frac{\pi x}{a})\cos(\frac{2\pi y}{b})\right] \\ B_2 &= \frac{E_k z|A|}{1+\mu_k}\sqrt{\left[\frac{\pi^2}{a^2} y\cos(\frac{2\pi x}{a})\sin^2(\frac{\pi y}{b}) - \frac{\pi}{b}\sin^2(\frac{\pi x}{a})\sin(\frac{2\pi y}{b}) - \frac{\pi^2}{b^2} y\sin^2(\frac{\pi x}{a})\cos(\frac{2\pi y}{b})\right]^2 + \left[\frac{\pi}{a}\sin(\frac{2\pi x}{a})\sin^2(\frac{\pi y}{b}) + \frac{\pi^2}{ab} y\sin(\frac{2\pi x}{a})\sin(\frac{2\pi y}{b})\right]^2} \end{aligned}\right\}$$

Assuming that the failure of the water-resistant strata is caused by shear stress under the action of polyaxial stress and in accordance with the Mohr–Coulomb yield criterion, we have

$$\sigma_1 - K\sigma_3 = R_c, \tag{6}$$

where $\varphi$ is the internal angle of friction, $R_c$ is the uniaxial compressive strength of the water-resistant key strata, $C$ is cohesion, and $R_c = 2C\cos\varphi/(1 - \sin\varphi)$, $K = (1+\sin\varphi)/(1 - \sin\varphi)$ and:

$$f(x,y) = \frac{\sigma_1 - K\sigma_3}{R_c}. \tag{7}$$

We use the ratio of the function $f$(x, y) if some point yield failures in the inclined water-resistant strata can be determined and its stability can be predicted as well. Substituting Eq. (5) into Eq. (7), the function $f(x, y)$ can be expressed as:

$$\begin{aligned} f(x,y) = \frac{E_k h_k}{2R_c}\Bigg\{ & \frac{(1-K)A}{1-\mu_k}\left[\frac{\pi^2}{a^2} y\cos(\frac{2\pi x}{a})\sin^2(\frac{\pi y}{b}) + \frac{\pi}{b}\sin^2(\frac{\pi x}{a})\sin(\frac{2\pi y}{b}) + \frac{\pi^2}{b^2} y\sin^2(\frac{\pi x}{a})\cos(\frac{2\pi y}{b})\right] \\ & + \frac{(1+K)|A|}{1+\mu_k}\sqrt{\left[\frac{\pi^2}{a^2} y\cos(\frac{2\pi x}{a})\sin^2(\frac{\pi y}{b}) - \frac{\pi}{b}\sin^2(\frac{\pi x}{a})\sin(\frac{2\pi y}{b}) - \frac{\pi^2}{b^2} y\sin^2(\frac{\pi x}{a})\cos(\frac{2\pi y}{b})\right]^2 + \left[\frac{\pi}{a}\sin(\frac{2\pi x}{a})\sin^2(\frac{\pi y}{b}) + \frac{\pi^2}{ab} y\sin(\frac{2\pi x}{a})\sin(\frac{2\pi y}{b})\right]^2}\Bigg\} \end{aligned} \tag{8}$$

**Table 1** General range of parameters for geologic setting and mining operation

| Parameters | Symbol | General range |
|---|---|---|
| Initial or 1–2 periodic weighting distance of stope | $a$ | 30–60/m |
| Inclination length of workface | $b$ | 80–200/m |
| Height of caved overburden | $h_0$ | 0–10/m |
| Depth of water-conducting fractured zone | $h_1$ | 5–25/m |
| Thickness of confining layer | $h_2$ | 0–30/m |
| Height of zone of water rising from the confined aquifer as mining progresses | $h_3$ | 0–15/m |
| Thickness of water-resistant key strata | $h_k$ | 6–12/m |
| Thickness of confining layer above water-resistant key strata | $h_{21}$ | 0–20/m |
| Dip angle of water-resistant key strata | $\beta$ | 0–45/° |
| Water pressure of floor confined aquifer | $P_o$ | 0–5/MPa |
| Bulk density of stope strata | $\gamma_0, \gamma_1, \gamma_2, \gamma_k$ | 5–35/kN·m$^{-3}$ |
| Uniaxial compressive strength of water-resistant key strata | $R_c$ | 20–180/MPa |
| Uniaxial tensile strength of water-resistant key strata | $R_t$ | 2–18/MPa |
| Elasticity modulus of water-resistant key strata | $E_k$ | 10–40/GPa |
| Cohesive strength of water-resistant key strata | $C$ | 5–45/MPa |
| Internal friction angle of water-resistant key strata | $\varphi$ | 10–50/° |
| Poisson's ratio of water-resistant key strata | $\mu_k$ | 0.1–0.3 |

**Table 2** The maximum value and location of the isocline contour of function *f*(x, y) for different parameters

| No. | Parameter values of function *f*(x, y) obtained by $L_{16}(4^5)$ orthogonal design | | | | | Maximum value | Position coordinates of maximum value/m | Normalized position coordinates/m |
|---|---|---|---|---|---|---|---|---|
| | $a$/m | $b$/m | $h_k$/m | $\beta$/ ° | $E_k$/GPa | | | |
| 1 | 30 | 80 | 6 | 0 | 10 | 1.870 | (0, 46.9) | (0, 1.84b/π) |
| | | | | | | | (30, 46.9) | ($a$, 1.84$b$/π) |
| 2 | 30 | 120 | 8 | 15 | 20 | 1.202 | (0, 70.3) | (0, 1.84b/π) |
| | | | | | | | (30, 70.3) | ($a$, 1.84$b$/π) |
| 3 | 30 | 160 | 10 | 30 | 30 | 0.879 | (0, 93.7) | (0, 1.84b/π) |
| | | | | | | | (30, 93.7) | ($a$, 1.84$b$/π) |
| 4 | 30 | 200 | 12 | 45 | 40 | 0.709 | (0, 117.2) | (0, 1.84b/π) |
| | | | | | | | (30, 117.2) | ($a$, 1.84$b$/π) |
| 5 | 40 | 80 | 8 | 30 | 40 | 1.838 | (0, 46.9) | (0, 1.84b/π) |
| | | | | | | | (40, 46.9) | ($a$, 1.84$b$/π) |
| 6 | 40 | 120 | 6 | 45 | 30 | 4.382 | (0, 70.3) | (0, 1.84b/π) |
| | | | | | | | (40, 70.3) | ($a$, 1.84$b$/π) |
| 7 | 40 | 160 | 12 | 0 | 20 | 0.841 | (0, 93.7) | (0, 1.84b/π) |
| | | | | | | | (40, 93.7) | ($a$, 1.84$b$/π) |
| 8 | 40 | 200 | 10 | 15 | 10 | 1.427 | (0, 117.2) | (0, 1.84b/π) |
| | | | | | | | (40, 117.2) | ($a$, 1.84$b$/π) |
| 9 | 50 | 80 | 10 | 45 | 20 | 1.652 | (0, 46.9) | (0, 1.84b/π) |
| | | | | | | | (50, 46.9) | ($a$, 1.84$b$/π) |
| 10 | 50 | 120 | 12 | 30 | 10 | 1.401 | (0, 70.3) | (0, 1.84b/π) |
| | | | | | | | (50, 70.3) | ($a$, 1.84$b$/π) |
| 11 | 50 | 160 | 6 | 15 | 40 | 5.972 | (0, 93.7) | (0, 1.84b/π) |
| | | | | | | | (50, 93.7) | ($a$, 1.84$b$/π) |
| 12 | 50 | 200 | 8 | 0 | 30 | 3.091 | (0, 117.2) | (0, 1.84b/π) |
| | | | | | | | (50, 117.2) | ($a$, 1.84$b$/π) |
| 13 | 60 | 80 | 12 | 15 | 30 | 1.110 | (0, 46.9) | (0, 1.84b/π) |
| | | | | | | | (60, 46.9) | ($a$, 1.84$b$/π) |
| 14 | 60 | 120 | 10 | 0 | 40 | 2.279 | (0, 70.3) | (0, 1.84b/π) |
| | | | | | | | (60, 70.3) | ($a$, 1.84$b$/π) |
| 15 | 60 | 160 | 8 | 45 | 10 | 5.579 | (0, 93.7) | (0, 1.84b/π) |
| | | | | | | | (60, 93.7) | ($a$, 1.84$b$/π) |
| 16 | 60 | 200 | 6 | 30 | 20 | 9.924 | (0, 117.2) | (0, 1.84b/π) |
| | | | | | | | (60, 117.2) | ($a$, 1.84$b$/π) |

**Table 3** Other parameter values for calculation

| $h_0$ | $h_1$ | $h_{21}$ | $\gamma_0$ | $\gamma_1$ | $\gamma_2$ | $\gamma_k$ | $\mu_k$ | $\varphi$ | $C$ | $\rho$ | $g$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 m | 17 m | 10 m | 22 kN·m$^{-3}$ | 23 kN·m$^{-3}$ | 24 kN·m$^{-3}$ | 28 kN·m$^{-3}$ | 0.24 | 46° | 15 MPa | $10^3$/kg·m$^{-3}$ | 10/N·kg$^{-1}$ |

Before mining, the strata of the inclined coal seam floor is in equilibrium. However, the stress state of the floor strata changes during mining. When the water-resistant key strata in the inclined coal seam floor deform and bend upward due to the combined action of mining and water pressure, water inrush vents can occur. By drawing the isocline contour of function *f*(*x, y*), the position with the maximum ratio of $(\sigma_1 - K\sigma_3)/R_c$ in the key strata can be determined, and the water-resistant key strata can fail most easily at this point.

At present, when the coal seam is 50° or less, the workface is frequently arranged with respect to the fully mechanized longwall workface, and the roof of the stope is managed by caving. Table 1 shows the parameter range for the geologic setting and mining operation, based on the site engineering data. Furthermore, experience in the mine shows that a hard confining layer stratum over 12 m thick prevents water inrush through the floor. When no such strata exists or the thickness of the confining layer is less than 6 m, the water-isolating capacity of the confining layer is poor, and water inrush from floor may occur. Thus, the current study focuses on the stability and water-isolating capacity of the water-resistant key strata with a thickness of 6–12 m, and predicts water inrush from an inclined coal seam floor.

We selected five main influential factors from the parameter range of geologic setting and mining operation in Table 1: the workface advanced distance *a*, tilted length of workface *b*, thickness $h_k$ of water-resistant key strata, and its pitch $\beta$ and elasticity modulus $E_k$. Then, we divided the parameter range of each factor into four levels. Using the $L_{16}(4^5)$ orthogonal design, we designed a 16-group scheme (Table 2), and drew the isocline contour of function *f*(x, y) using Eq. (8), the other parameters shown in Table 3, and $z = h_k/2$. Through the isocline contours of function *f*(x, y), we defined where the function *f*(x, y) at the downward position at the midpoint of the long side of the inclined floor water-resistant key strata was at its maximum (Table 2), which indicates where the key strata was most likely to fail because of shear failure. Notably, the long side of the water-resistant key strata is the tilted direction along the workface at a length of *b*, whereas the short side is the workface advancing direction with a width of *a* (Fig. 2a). For the fully mechanized longwall workface in China, the tilted length of workface *b* is generally greater than the workface advanced distance *a* (weighting step).

The position coordinates of points that are most likely to lead to failure were normalized to (0, 1.84*b*/π) and (*a*, 1.84*b*/π), as shown in Table 2. We replaced these coordinates in Eq. (8), giving:

$$f(x,y) = \frac{\frac{0.92\pi h_k E_k b^2 (1-\sin\varphi)(K-\mu_k)\sin^2(1.84)}{a^2 C(1-\mu_k^2)\cos\varphi}\left\{P_0 + \left(\frac{2}{3} - \frac{1}{\pi^2}\right)\rho g b \sin\beta - \left(\gamma_0 h_0 + \gamma_1 h_1 + \gamma_2 h_{21} + \gamma_k h_k\right)\cos\beta\right\}}{\frac{E_k h_k^3}{6(1-\mu_k^2)}\left[\left(\frac{\pi}{a}\right)^4 b^2\left(1 - \frac{15}{8\pi^2}\right) + \left(\frac{\pi}{b}\right)^2\left(\pi^2 + \frac{15}{8}\right) + \left(\frac{\pi}{a}\right)^2\left(\frac{2}{3}\pi^2 - \frac{1}{4}\right)\right]}. \tag{9}$$

Equation (9) shows the stability mechanics criterion of the inclined floor water-resisting key strata. When *f*(*x*, *y*) < 1, the inclined water-resistant key strata remains stable; when *f*(*x*, *y*) = 1, these strata are in a critical state; and when *f*(*x*, *y*) > 1, the strata are in an unstable state.

**Table 4** Water pressure $P_m$ obtained using a $L_{16}(4^5)$ orthogonal design

| No. | Parameter values of Eq. (10) obtained by $L_{16}(4^5)$ orthogonal design | | | | | Water pressure $P_m$/MPa |
|---|---|---|---|---|---|---|
| | *a*/m | *b*/m | $h_k$/m | *β*/ ° | $E_k$/GPa | |
| 1 | 30 | 80 | 6 | 0 | 10 | 2.274 |
| 2 | 30 | 120 | 8 | 15 | 20 | 3.031 |
| 3 | 30 | 160 | 10 | 30 | 30 | 3.927 |
| 4 | 30 | 200 | 12 | 45 | 40 | 4.964 |
| 5 | 40 | 80 | 8 | 30 | 40 | 2.165 |
| 6 | 40 | 120 | 6 | 45 | 30 | 0.900 |
| 7 | 40 | 160 | 12 | 0 | 20 | 3.966 |
| 8 | 40 | 200 | 10 | 15 | 10 | 2.647 |
| 9 | 50 | 80 | 10 | 45 | 20 | 2.265 |
| 10 | 50 | 120 | 12 | 30 | 10 | 2.657 |
| 11 | 50 | 160 | 6 | 15 | 40 | 1.086 |
| 12 | 50 | 200 | 8 | 0 | 30 | 1.755 |
| 13 | 60 | 80 | 12 | 15 | 30 | 3.240 |
| 14 | 60 | 120 | 10 | 0 | 40 | 2.083 |
| 15 | 60 | 160 | 8 | 45 | 10 | 0.636 |
| 16 | 60 | 200 | 6 | 30 | 20 | 0.517 |

**Table 5** Analysis of maximum allowable water pressure $P_m$ obtained by $L_{16}(4^5)$ orthogonal design

| Orthogonal parameters | $\sum L_1$ | $\sum L_2$ | $\sum L_3$ | $\sum L_4$ | $\overline{\sum L_1}$ | $\overline{\sum L_2}$ | $\overline{\sum L_3}$ | $\overline{\sum L_4}$ | $R$ | Influence degree (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| $a$ | 14.196 | 9.678 | 7.763 | 6.475 | 3.549 | 2.420 | 1.941 | 1.619 | 1.930 | 34.4 |
| $b$ | 9.944 | 8.671 | 9.615 | 9.884 | 2.486 | 2.168 | 2.404 | 2.471 | 0.318 | 5.7 |
| $h_k$ | 4.777 | 7.587 | 10.922 | 14.827 | 1.194 | 1.897 | 2.731 | 3.707 | 2.513 | 44.8 |
| $\beta$ | 10.078 | 10.004 | 9.266 | 8.765 | 2.520 | 2.501 | 2.317 | 2.191 | 0.329 | 5.8 |
| $E_k$ | 8.214 | 9.779 | 9.822 | 10.298 | 2.053 | 2.445 | 2.456 | 2.575 | 0.522 | 9.3 |

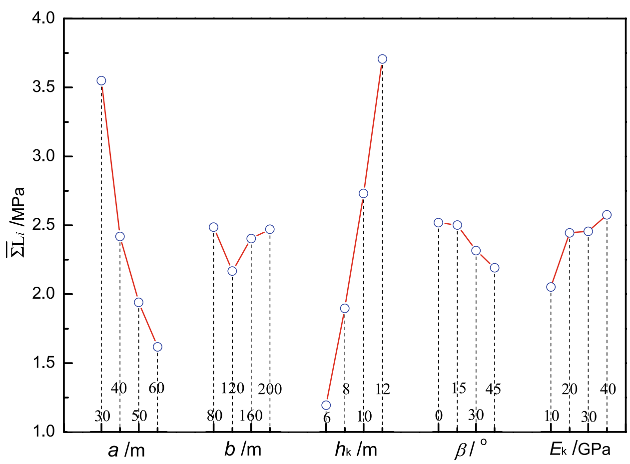


**Fig. 3** Relationship among five factors and the average value of each for each level

Assuming that Eq. (9) $f(x, y) = 1$, we obtain the following equation:

$$P_m = \frac{a^2 C(1-\mu_k^2)\cos\varphi}{0.92\pi h_k E_k b^2 (1-\sin\varphi)(K-\mu_k)\sin^2(1.84)} \left\{ \frac{E_k h_k^3}{6(1-\mu_k^2)} \left( (\frac{\pi}{a})^4 b^2 (1 - \frac{15}{8\pi^2}) + (\frac{\pi}{b})^2 (\pi^2 + \frac{15}{8}) + (\frac{\pi}{a})^2 (\frac{2}{3}\pi^2 - \frac{1}{4}) \right) - \frac{3b(\gamma_0 h_0 + \gamma_1 h_1 + \gamma_2 h_{21} + \gamma_k h_k)\sin\beta}{8} \left(\pi^2 - \frac{9}{4}\right) \right\} \quad (10)$$

In Eq. (10), $P_m$ is the maximum water pressure that the inclined floor water-resistant key strata can take. Under the combined process of mining and water pressure, when the maximum allowable water pressure $P_m$ exceeds the water pressure $P_o$ of the confined aquifer, the key strata is stable, and water inrush does not occur. When the maximum allowable water pressure $P_m$ is equal to the water pressure $P_o$ of the confined aquifer, the inclined key strata are in a critical state and the likelihood of water inrush is high.

## Factors that Influence the Water-Isolating Capacity

### Analysis Based on the Multi-factor Method

We divided the parameter range of each of the five most influential factors from Table 1 into four levels (Table 4) and obtained the maximum water pressure $P_m$ that the water-resistant key strata can take by using Eq. (10), as shown in Table 4, and the other parameters shown in Table 3. Table 4 shows that when the water pressure $P_o$ of the confined aquifer is 3.5 MPa, only the maximum allowable water pressure $P_m$ calculated by the parameter values of schemes 3, 4, and 7 exceed 3.5 MPa, which indicates that the water-resistant key strata are stable, and water inrush should not occur.

Table 4 separately sums up the water pressure $P_m$ of four levels of the five most influential factors. Furthermore, Table 5 provides the summed values $\sum L_i$ ($i = 1, 2, 3, 4$) and their corresponding average values $\overline{\sum L_i}$. In Table 5, $R$ ($R = \max \overline{\sum L_i} - \min \overline{\sum L_i}$) is range, which reflects the change amplitude of the test results when a factor changes. From the range $R$ in Table 5, the order of factors that influence the water-isolating capacity of the water-resistant key strata can be concluded. The thickness $h_k$ of the key strata was the most important factor, with a 44.8% ranking, followed by the distance that the workface had advanced $a$, at 34.4%. The influence of the elasticity modulus $E_k$, pitch $\beta$, and the tilted length of the workface $b$, were 9.3, 5.8, and 5.7%, respectively. Thus, the maximum water pressure $P_m$ that the strata can take is highly sensitive to the thickness $h_k$

of the water-resistant key strata, and is relatively insensitive to the tilted length of workface $b$.

Figure 3 shows the relationship between the five factors ($a$, $b$, $h_k$, $\beta$, and $E_k$) and the average values of $\overline{\sum L_i}$ of the four levels. The average values of $\overline{\sum L_i}$ decrease rapidly with increasing values of $a$, which means that when the workface advanced distance increases, the maximum water pressure $P_m$ that the inclined strata can tolerate decreases. As $b$ increases, the average values of $\overline{\sum L_i}$ first decrease, and then slowly increase. This is because of the thickness of $h_k$ of the water-resistant key strata in the third and fourth levels of the influential factor $b$ (Table 4), i.e. schemes 3, 4, and 7. The previous analysis showed that the maximum water pressure $P_m$ that the inclined strata can withstand is highly sensitive to the thickness of the key strata; thus, the average values of $\overline{\sum L_i}$ slowly increase in the third and fourth levels of $b$. If we weaken the leading role of the thickness of the key strata in the third and fourth levels, the maximum water pressure that the key strata can tolerate decreases with the increasing length of the workface for the same value of $a$. The average values of $\overline{\sum L_i}$ increase quickly with the increased thickness of the water-resistant key strata; the greater the thickness, the better the water-isolating capacity. The average values $\overline{\sum L_i}$ decrease with the increasing pitch of the strata, which means that the maximum water pressure that the inclined floor water-resistant key strata can tolerate decreases as $\beta$ increases; that is, the greater the pitch, the greater the risk. The average values of $\overline{\sum L_i}$ increase as the value of $E_k$ increases; the higher the elasticity

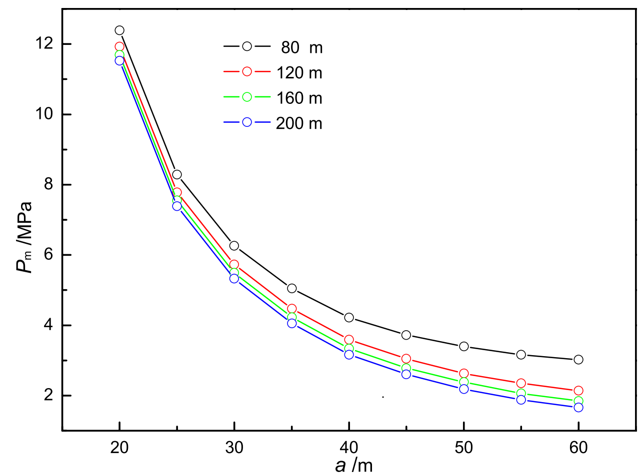


**Fig. 5** Relationship between the maximum water pressure $P_m$ that the inclined water-resistant key strata can tolerate and its size $a$ and $b$ (where $h_k$=12 m, $\beta$=30°, $E_k$=32 GPa; other parameters are shown in Table 3)

modulus, the better the water-isolating capacity of the key strata.

## Analysis Based on the Single-factor Method

### *Load of Caved Overburden*

Figure 4 shows that the maximum water pressure that the water-resistant key strata can tolerate increases as the load of caved overburden increases, indicating that the

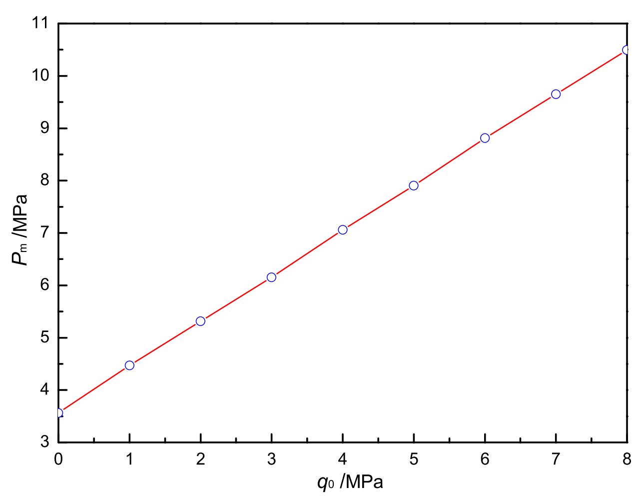


**Fig. 4** Relationship between the maximum water pressure $P_m$ that the inclined water-resistant key strata can tolerate and the caved overburden load $q_0$ (where $a$=40 m, $b$=120 m, $h_k$=12 m, $\beta$=30°, $E_k$=32 GPa; other parameters are shown in Table 3)

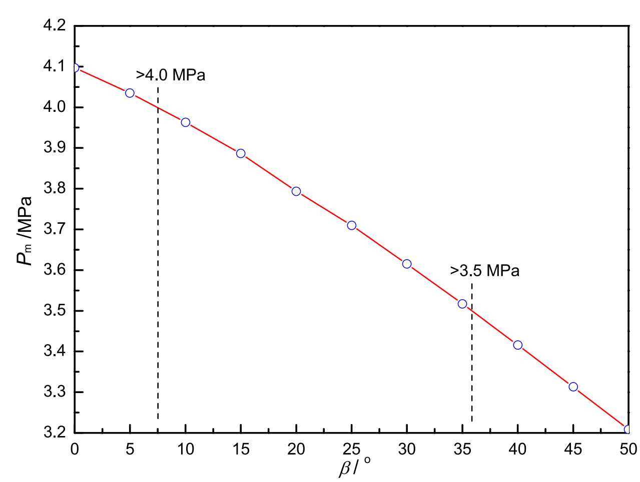


**Fig. 6** Relationship between the maximum water pressure $P_m$ that the water-resistant key strata can tolerate and its pitch $\beta$ (where $a$=40 m, $b$=120 m, $h_k$=12 m, $E_k$=32 GPa; other parameters are shown in Table 3)

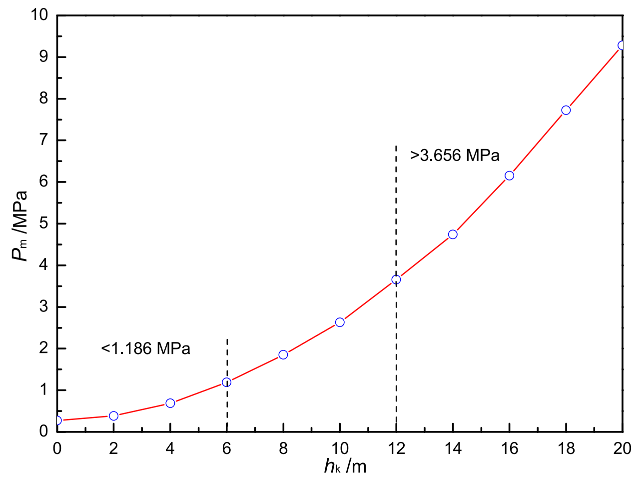


**Fig. 7** Relationship between the maximum water pressure $P_m$ that the water-resistant key strata can tolerate and its thickness $h_k$ (where $a=40$ m, $b=120$ m, $\beta=30°$, $E_k$=32 GPa; other parameters are shown in Table 3)

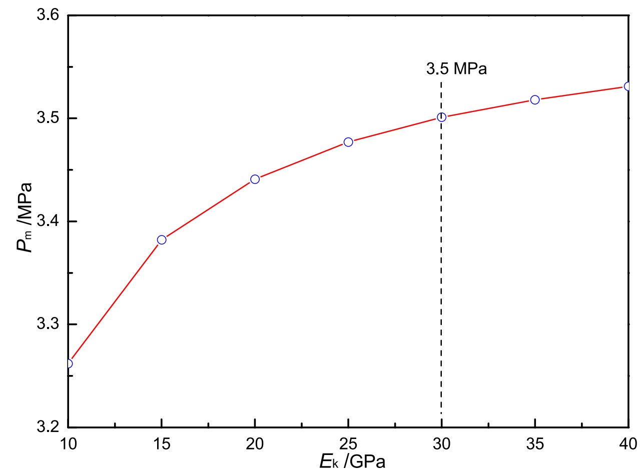


**Fig. 9** Relationship between the maximum water pressure $P_m$ that the water-resistant key strata can tolerate and the elasticity modulus $E_k$ of the water-resistant key strata (where $a=40$ m, $b=120$ m, $h_k$=12 m, $\beta=30°$; other parameters are shown in Table 3)

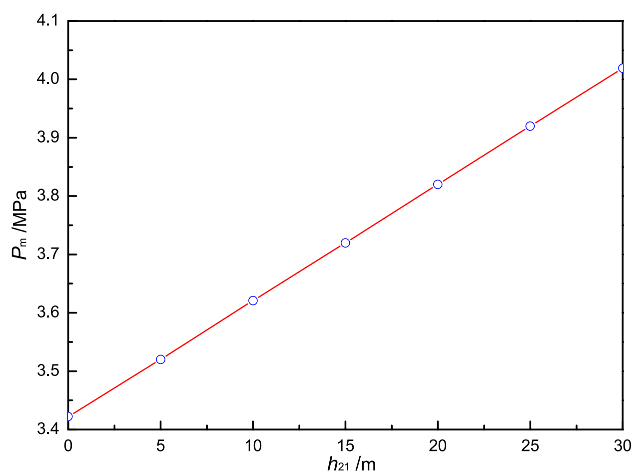


**Fig. 8** Relationship between the maximum water pressure $P_m$ that the water-resistant key strata can tolerate and the thickness $h_{21}$ of the confining layer lying above the water-resistant key strata (where $a=40$ m, $b=120$ m, $h_k$=12 m, $\beta=30°$, $E_k$=32 GPa; other parameters are shown in Table 3)

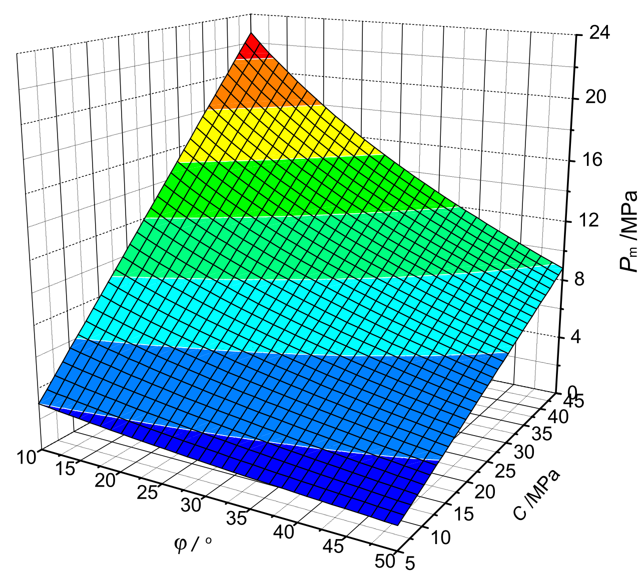


**Fig. 10** Relationship between the maximum water pressure $P_m$ that the water-resistant key strata can tolerate and the cohesive strength $C$ and internal friction angle $\varphi$ of the water-resistant key strata (where $a=40$ m, $b=120$ m, $h_k$=12 m, $\beta=30°$, $E_k$=32 GPa; other parameters are shown in Table 3)

collapsed overburden offers some protection from floor water inrush.

### *Weighting Distance of Stope and Size of Water-resistant Key Strata*

Instability of water-resistant key strata, which induces water inrush through the coal seam floor, is closely related to the ground pressure of the stope (Zhang and Wang 1997). To study the relationship between the stability of the key strata and the initial or periodic weighting distance of the stope, the size of the goaf before the initial pressure was applied to be equivalent to the size of the key strata. The length of the inclined floor water-resistant key strata is the length of the tilted direction of the workface, and the width is the distance of the initial or 1–2 periodic weighting distance of the stope. As shown in Fig. 5, the maximum water pressure that the water-resistant key strata can tolerate decreases with increasing values of $a$ for different values of $b$. This means that when the initial or periodic weighting distance becomes large, floor water inrush can more easily occur due to the suspended main roof strata. Furthermore, the maximum allowable water pressure increases with decreasing lengths of $b$ for the same workface advanced distance. Therefore, prevention of water inrush from the floor can be achieved through proper control of the weighting distance and the length of the workface.

*Pitch of Water-resistant Key Strata*

As can be observed in Fig. 6, where the maximum allowable water pressure decreases with the increasing pitch of the water-resistant key strata. The reason is that the lateral load $q\cos\beta$ acting on the surface of the water-resistant key strata, part of vertical downward load $q$, decreases with the increase in dip angle, whereas the longitudinal load $q\sin\beta$ acting on the side of the water-resistant key strata, increases, as shown in Fig. 2b. Simultaneously, the hydraulic gradient along the slope direction acting on the lower surface of the key strata increases slightly, and the water-isolating capacity of the key strata decreases. When the pitch $\beta$ is less than 7.5°, the maximum allowable water pressure $P_m$ is greater than 4.0 MPa; and when the pitch $\beta$ is less than 36°, the $P_m$ is greater than 3.5 MPa, as shown in Fig. 6. Therefore, the greater the pitch of floor strata, the greater the risk of floor water inrush.

*Thickness and Location of Water-resistant Key Strata*

A parabolic relationship exists between the maximum allowable water pressure $P_m$ and the thickness $h_k$ (Fig. 7). When $h_k$ is less than 6 m, $P_m$ is less than 1.19 MPa, and when $h_k$ is over 12 m, $P_m$ exceeds 3.66 MPa, which indicates that the maximum allowable water pressure is sensitive to the value of $h_k$. Thus, the greater the thickness, the better the water-isolating capacity, which is consistent with the statistical results of water inrush from the floor.

As shown in Fig. 8, the greater the thickness of the confining layer above the water-resistant key strata, the greater the maximum allowable water pressure. As $h_{21}$ grows thicker, the downward load acting on the key strata grows stronger, increasing $P_m$. So, if the water-resistant key strata lies within the lower part of the confining layer, it offers improved protection from floor water inrush.

*Strength of Water-resistant Key Strata*

The relationship between $P_m$ and the elasticity modulus $E_k$ of the water-resistant key strata in Fig. 9 shows that the maximum water pressure that can be tolerated by the inclined key strata increases as $E_k$ increases. When $E_k$ is 30 GPa, the $P_m$ is 3.5 Mpa. This is because the rock mass strengthens as its elastic modulus increases.

Figure 10 shows that the maximum allowable water pressure increases with its increasing cohesive strength, $C$. The rock mass strengthens as $C$ increases, and so is less easily destroyed under pressure. However, as the internal friction angle, $\varphi$, grows, $P_m$ slightly decreases because the larger $\varphi$ is, the more fragile the rock is. Thus, water-resistant key strata formed by a single hard rock layer can resist strong deformation, but can easily induce water inrush after breaking. Water-resistant key strata formed of both hard and soft rock have a higher deformation tendency, but is less susceptible to destruction, since the soft rock can seal the fractures generated in the hard rock, increasing its ability to prevent water inrush (Miao et al. 2007, 2008).

## Engineering Application Method

To analyze the stability and water-isolating capacity of water-resistant key strata in an inclined coal seam floor, we must first determine the thickness, strength, and location of each layer, including the water pressure distribution of the confined aquifers, with multi-drilling geological data and rock mechanics testing to determine the values of $h$, $h_3$, $\beta$, $P_o$, $\gamma_0$, $\gamma_1$, $\gamma_2$, $\rho$, and $g$. Then, using the identification method of structural key strata, we can judge the water-resistant key strata of the coal seam floor and determine the lithology, thickness, density, strength (compressive strength, tensile strength, and shear strength), as well as the other strata parameters to determine the values of $h_k$, $\gamma_k$, $E_k$, $R_c$, $R_t$, $C$, $\varphi$, and $\mu_k$. The lithology, thickness, density, strength, location, and other parameters of structural key strata generally vary in different geological environments.

Third, considering the geologic setting and activities at the adjacent workface, we can determine the parameter values of $a$, $h_0$, $h_1$, $h_2$, $h_{21}$, and $h_{22}$. Finally, using Eq. (10), we can determine the appropriate values of $b$ using the orthogonal design and thereby ensure mine safety above the confined aquifers. Using these parameter values, the proposed water-resistant key strata model and its stability criterion can be expanded for other regions with inclined coal seam floors.

## Summary and Conclusions

Water inrush from the coal seam floor is a problem that seriously threatens safety mining in China. A model of an inclined coal seam floor with linearly increasing water pressure was established based on theories of ground pressure and key strata, and stability metrics were developed for the water-resistant key strata. Five principle influential factors were selected for sensitivity analysis using the orthogonal design: the thickness of the key strata was the most important factor, with a 44.8% ranking, followed by the distance that the workface had advanced at 34.4%, and then the influence of the elasticity modulus, pitch, and tilted length of the workface, at 9.3, 5.8, and 5.7%, respectively.

Our results indicate that the maximum water pressure that the inclined floor water-resistant key strata can tolerate increases with additional caved overburden loading, and the caved overburden can provide improved protection from floor water inrush. The maximum allowable water pressure decreases with an increased initial or periodic weighting distance and the length of workface. Water inrush from the floor can be prevented by appropriate control of the weighting distance and workface length. The maximum allowable water pressure decreases with the increasing pitch of the key strata; that is, the greater the pitch, the greater the risk. Otherwise, a parabolic relationship exists between the maximum allowable water pressure and the thickness of the water-resistant key strata; that is, the greater the thickness, the better the water-isolating capacity. Water-resistant key strata located within the lower portion of the confining layer gives greater protection from floor water inrush events and the greater its strength, the higher the strength, the better its water-isolating capacity. These findings can provide an important theoretical basis to determine water inrush from an inclined coal seam floor when mining is conducted above confined aquifers.

Notably, we only investigated the water-isolating capacity of water-resistant key strata in an inclined coal seam floor and did not relate findings to the permeability characteristics of the water-resistant key strata. If the water-resistant key strata is fractured, it can form a seepage water inrush channel. When the seepage of the fracture and channel is stable, water-resistant key strata can still prevent water inrush from the floor, but when the seepage is unstable, water inrush may occur. Therefore, we recommend further research on the permeability characteristics of water-resistant key strata after it is fractured.

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## References

Abdelghani FB, Aubertin M, Simon R, Therrien R (2015) Numerical simulations of water flow and contaminants transport near mining wastes disposed in a fractured rock mass. Int J Min Sci Tech 25(1):37–45

Chaulya SK (2003) Assessment and management of water resources for a lignite mine. Mine Water Environ 22:45–51

Fan GW, Zhang DS (2015) Mechanisms of aquifer protection in underground coal mining. Mine Water Environ 34:95–104

Feng QY, Li T, Qian B, Zhou L, Gao B, Yuan T (2014) Chemical characteristics and utilization of coal mine drainage in China. Mine Water Environ 33:276–286

Han J, Shi LQ, Yu XG, Wei JC, Li SC (2009) Mechanism of mine water-inrush through a fault from the floor. Min Sci Tech 19(3):276–281

James P, Dave C (2015) Current research on mine water and the environment in New Zealand. Mine Water Environ 34:363

Kong HL, Miao XX, Wang LZ, Zhang Y, Chen ZQ (2007) Analysis of the harmfulness of water-inrush from coal seam floor based on seepage instability theory. J China Univ Min Tech 17(4):453–458

Li BY (1999) "Down Three Zones" in the prediction of water inrush from coalbed floor aquifer-theory, development and application. J Shandong Inst Min Tech 18(4):11–18

Li LP, Zhou ZQ, Li SC, Xue YG, Xu ZH, Shi SS (2015) An attribute synthetic evaluation system for risk assessment of floor water inrush in coal mines. Mine Water Environ 34:288–294

Liang DX, Jiang ZQ, Guan YZ (2015) Field research: measuring water pressure resistance in a fault-induced fracture zone. Mine Water Environ 34:320–328

Meng Z, Li G, Xie X (2012) A geological assessment method of floor water inrush risk and its application. Eng Geol 143–144:51–60

Miao XX, Liu WQ, Chen ZQ (2004) Seepage theory in mining rock. Science, Beijing

Miao XX, Chen RH, Bai HB (2007) Fundamental concepts and mechanical analysis of water-resisting key strata in water preserved mining. J China Coal Soc 32(6):561–564

Miao XX, Pu H, Bai HB (2008) Principle of water-resisting key strata and its application in water-preserved mining. J China Univ Min Tech 37(1):1–4

Qian MG, Shi PW (2003) Ground pressure and strata control. China University of Mining and Technology Press, Xuzhou

Qian MG, Miao XX, Xu JL, Mao XB (2003) Key strata theory in ground control. China University of Mining and Technology Press, Xuzhou

Sun J, Wang LG (2014) Instability mechanics criterion of inclined water-resisting key strata in coal seam floor. J China Coal Soc 39(11):2276–2285

Sun J, Wang LG, Tang FR, Shen YF, Gong SL (2011) Microseismic monitoring on the failure characteristics of an inclined coal seam floor. Rock Solid Mech 32(5): 1589–1595

Timoshenko SP, Woinowsky-Krieger SW (1959) Theory of Plates and Shells. McGraw-Hill Press, New York **(American)**

Wang JA, Park HD (2003) Coal mining above a confined aquifer. Int J Rock Mech Min Sci 40(4):537–551

Wang Q, Wang XY, Hou QL (2015) Geothermal water at a coal mine: from risk to resource. Mine Water Environ 34:1–8

Wu Q, Zhou W (2008) Prediction of groundwater inrush into coal mines from aquifers underlying the coal seams in China: vulnerability index method and its construction. Environ Geol 55(4):245–254

Wu Q, Wang MY, Wu X (2004) Investigations of ground water bursting into coal mine seam floors from fault zones. Int J Rock Mech Min 41(4):557–571

Wu Q, Zhou WF, Zhang L (2011) China's environment: challenges and solutions. Environ. Earth Sci 64:1503–1504

Wu Q, Fan S, Zhou W, Liu S (2013) Application of the analytic hierarchy process to assessment of water inrush a case study for the no. 17 coal seam in the Sanhejian coal mine, China. Mine Water Environ 32:229–238

Wu Q, Fan ZL, Zhang ZW, Zhou WF (2014) Evaluation and zoning of groundwater hazards in Pingshuo No.1 underground coal mine, Shanxi Province, China. Hydrogeol J 22:1693–1705

Wu Q, Xu SH, Zhou WF, James W (2015) Hydrogeology and design of groundwater heat pump systems. Environ. Earth Sci 73:3683–3695

Xu ZL (2006) Elasticity mechanics. Higher Education, Beijing

Xu JP, Liu SD, Wang B, Zhang P, Gui H (2012) Electrical monitoring criterion for water flow in faults activated by mining. Mine Water Environ 31:172–178

Yang C, Liu SD, Liu L (2016) Water abundance of mine floor limestone by simulation experiment. Int J Min Sci Tech 26(3):495–500

Yin SX, Zhang J (2005) Impacts of karst paleo-sinkholes on mining and environment in northern China. Environ Geol 48(8):1077–1083

Yu BY, Chen ZQ, Yu LL (2016) Water-resisting ability of cemented broken rocks. Int J Min Sci Tech 26(3):449–454

Zhang JC (2005) Investigations of water inrushes from aquifers under coal seams. Int J Rock Mech Min Sci 42(3):350–360

Zhang XM, Wang XH (1997) The relationship of coal roof pressure and water-inrush from floor. Coal Geol Expl 25(supp.):51–53