**P-H-q evaluation system for risk assessment of water inrush in underground mining in North China coal field, based on rock-breaking theory and water-pressure transmission theory**

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**ABSTRACT**

Risk assessment of water inrush from a coal seam floor is essential for safety in many coal mines. From the point of view of mechanics, such water inrush forms on the floor when the aquiclude breaks under the action of continuous water pressure within a certain period of time. Consequently, the water from the aquifer below the aquiclude gushes along the rupture surface into the goaf. In this study, to clarify the water inrush mechanism, a time-related function \( f(P, H, q) \) is developed (where \( P \), \( H \), and \( q \) are the aquifer water pressure, aquifuge thickness, and aquifer specific yield, respectively). Hence, the likelihood of water inrush can be determined. Data collected from 150 cases are used to determine the related parameter thresholds. The influence of \( P \), \( H \), and \( q \) on water inrush occurrence is analysed based on the time-related function. Finally, a \( P-H-q \) evaluation system is proposed and successfully applied. The \( P-H-q \) evaluation system not only facilitates realistic risk assessment for water inrush, but also elucidates the water inrush mechanism in underground mining. The results also provide a reference for evaluating the risk of water inrush in other coal fields.

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1. Introduction

Coal has been and continues to be a major energy source in China. However, the exploitation of coal seams in the North China coal field is threatened by the underlying confined aquifers of the Taiyuan Formation limestone and Ordovician limestone. Thus, risk assessment of water inrush from the coal seam floor is essential to ensure the safety of many coal mines threatened by such hazards.

Water inrush from coal seam floors has been extensively studied in the past. For example, Wu et al. (2007a, 2007b, 2007c, 2009, 2015) proposed several practical methods for water-inrush risk assessment such as master-control index system construction, the vulnerable index method, combined use of geographic information systems (GIS) and artificial neural network (ANN) coupling technology, and the GIS-based analytic hierarchy program (AHP) vulnerable index method. In addition, Bai et al. (2013) used variable mass dynamics and nonlinear dynamics to explain groundwater inrush. A geological assessment method based on the mine lithology, structure, and conventional water-inrush coefficient \( T \) was successfully applied to evaluate floor water-inrush vulnerability at the Fangezhuang Coal Mine in China (Meng et al. 2012). Further, Liu and Hu (2011) employed the water-resisting coefficient of the rock layer to calculate the floor water-inrush hazard. Wang et al. (2012) constructed a secondary fuzzy comprehensive evaluation system to evaluate floor water-inrush vulnerability in...
coal mines, and Duan et al. (2012) established a coal floor water-inrush model that incorporates the floor aquiclude thickness, lithology, rock mass integrity, and expansive limits as indicators of anti-permeability strength. Further, Li et al. (2011) performed a numerical investigation of groundwater outbursts near faults in underground coal mines, providing highly meaningful guides for investigating the mechanism and preventing groundwater outbursts induced by faults in practice. Many other methods to evaluate and predict mine water inrush have been developed (Wildemeersch et al. 2010; Li CP et al. 2013; Li T et al. 2013; Shi et al. 2014; Wu et al. 2016; Bai et al. 2016; Qi et al. 2017). Most of the methods mentioned are multi-factor comprehensive evaluation methods. However, obtaining the necessary hydrogeological information to properly apply these methods is challenging in practice because of the various associated technical and geological conditions.

At present, the water-inrush coefficient method, i.e. the $T$ method, which is described in the Stipulations on Prevention and Control of Coal Mine Water (State Administration of Work Safety, State Administrate of Coal Mine Safety 2009), is the most practical technique for coal mines; thus, it is widely applied to assess floor water inrush risks. $T$ refers to the ratio of the water pressure ($P$) of the aquifers below the floor aquiclude to the floor aquiclude thickness ($H$). However, the $T$ method is over-simplified to allow water-inrush probability assessment and may yield false predictions. For example, water inrush does not occur in mines having very poor water richness in the aquifers below the floor aquiclude, or those having large $H$, even if $T$ exceeds the threshold value. The aquifer’s water richness can be represented by the aquifer specific yield ($q$). Therefore, it is necessary to consider both $q$ and $H$ to accurately assess the water inrush risk. Li et al. (2017) established an improved $T$ method, which incorporates $q$ and $H$. This improved $T$ method indicates that water inrush will not occur in mines having very small $q$ or large $H$. However, the specific influence of $q$ and $H$ on the occurrence of water inrush has not been further analysed.

In summary, traditional water-inrush evaluation methods include the $T$ method, improved $T$ method, and multi-factor comprehensive evaluation methods. The conventional $T$ method exclusively considers $P$ and $H$. Further, the critical water-inrush coefficient ($T_s$) specified in the $T$ method is invariant, and this condition neglects the influence of mining condition variations. Both the improved $T$ method and multi-factor comprehensive evaluation methods recognize that the occurrence of water inrush is not related to $P$ and $H$ alone, but is also influenced by factors such as $q$; thus, the various multi-factor comprehensive evaluation methods attribute different weights to each factor influencing the occurrence of water inrush. However, the specific role of each factor in the occurrence of water inrush has not been further analysed. Therefore, to elucidate the mechanism of water inrush from a coal seam floor, it is necessary to clarify the roles of the various hydrogeological factors. Hence, a more realistic water-inrush risk evaluation system can be established.

In this study, a time-related function $f(P, H, q)$ is derived in order to determine the likelihood of water inrush. The related parameter thresholds were determined from the data collected from 150 cases for the North China coal field. Hence, a $P-H-q$ evaluation system is proposed and successfully applied. The proposed system facilitates realistic risk assessment of water inrush, and it elucidates the water-inrush mechanism in underground mining. Because we selected cases of inrush located in the same coal field (viz., the North China coal field), the stratigraphic sedimentary characteristics, geological structure, and coal seam mining conditions were similar. As such, differences in the stratum, structure, and mining way were neglected in the analysis. Instead, factors $P$, $H$ and $q$ – i.e. factors directly involved in the process of water inrush – were emphasized in our analysis.

2. Concepts for describing water-inrush process

The relative positions of the goaf, aquiclude, and aquifer in the coal seam are shown in Figure 1. Water inrush occurs as the water from the aquifer breaks through the aquiclude above and proceeds into the goaf. Therefore, the water inrush process actually corresponds to aquiclude breaking under water pressure. To facilitate a detailed description of the water-inrush process, some related concepts are presented below.
First, deformation and breaking of the aquiclude must be complete before the goaf is filled and compacted by the broken overlying rock. The effect of the goaf filling condition on the water-inrush behaviour is shown in Figure 2. The time period before the goaf is filled and compacted can be called the available time \( t_a \) for water-inrush formation. After a goaf of length \( L \) is formed, the aquiclude gradually bends and deforms under the water pressure; the time required to bend the aquiclude to breaking point is called the required time \( t_r \). Water inrush can only occur in cases where \( t_a > t_r \).

Second, the water pressure that is continuously loaded on the aquiclude constitutes the external force directly responsible for eventually breaking the aquiclude. This water pressure is called the aquifuge bending pressure \( P_b \). \( P_b \) also refers to the pressure of the water accumulated in the cavity caused by aquifuge deformation, which is situated between the aquiclude and aquifer (③ in Figure 3). (Unless otherwise stated, this is the cavity referred to hereafter.) Note that \( P \) indicates the water pressure in the aquifer before mining, or the undisturbed water pressure in the undisturbed area of the aquifer after the coal seam has been mined. The water-pressure variation and water run-off in the aquifer after exploitation of the coal seam are shown in Figure 3. With increased \( P_b \), the degree of aquifuge bending gradually increases. The \( P_b \) that must be achieved for the aquiclude to break is the critical pressure for aquifuge breaking \( (P_b') \). Once the thickness and span of the aquifuge are determined, \( P_b' \) can be obtained. Obviously, because of the pressure difference between areas ① and ② in Figure 3, the relation \( 0 < P_b < P \) manifests during the aquiclude deformation process. The following relationships may occur between \( P, P_b, \) and \( P_b' \) when the aquiclude deformation is complete, or the aquiclude reaches its critical breaking state:

1. If the aquiclude is not eventually broken within \( t_a \), \( P_b = P < P_b' \) obtains when the aquiclude is no longer bent at a moment before reaching its critical breaking state;
2. If the aquiclude is not eventually broken within \( t_a \), \( P_b = P = P_b' \) obtains when the aquiclude reaches its critical breaking state but does not break;
3. If the aquiclude is eventually broken within \( t_a \), \( P_b = P_b' < P \) obtains when the aquiclude reaches its critical breaking state.

Therefore, the aquifuge can only be broken by the water pressure of the aquifers below the floor aquifuge within \( t_a \) if \( P \) is larger than \( P_b' \); then, water inrush occurs from the coal seam floor.

Third, the persistence of \( P_b \) is ensured by the water-pressure transmission due to continuous migration of water into the cavity. The water pressure driving the continuous water migration is called the driving pressure \( (P_d) \). As apparent from Figure 3, \( P_d \) also corresponds to the pressure difference between areas ① and ③.
Fourth, besides the size of $P_d$, the migration efficiency of the water in the aquifer is also related to the water conductivity of the aquifer itself. In hydrogeology, the water conductivity is expressed by the transmissibility coefficient, usually labelled ‘$T$.’ However, ‘$D$’ is used to represent the transmissibility coefficient in this study, to avoid confusion with the symbol for the water-inrush coefficient in the $T$ method. Thus, the water conductivity is also indicated by $D$.

In this study, systematic analyses of mining data acquired at 150 mining faces in the North China coal field were conducted (Figure 4). However, the collected data contained no information on $D$; thus, we attempted to replace $D$ with other related parameter. A linear positive correlation between $D$ and $q$ has been determined previously (see Section 3.3.2.); thus, the water-migration efficiency is also related to $q$. Therefore, the water conductivity is indicated by $q$ in this study.

Finally, based on the systematic analyses of the acquired mining data, the relationships between $P$, $P_{sb}$, and $P_{sb'}$, $H$ and $P_{sb'}$; $q$ and $P_{sb'}$ and $P$, $H$, $q$, and $t$, were determined. A $P$-$H$-$q$ evaluation system incorporating the relationships between $P$, $H$, $q$, $t_r$, and $t_a$ was then proposed.

Figure 2. Effect of goaf filling condition on water-inrush occurrence. (a) No water inrush occurs if goaf has been filled. (b) Water inrush occurs if goaf has not been filled.
3. Relationships between parameters influencing the occurrence of water inrush

3.1. Relationship between $P$, $P_b$, and $P_d$

As shown in Figure 3, $P_b$ and $P$ correspond to the water pressures in areas 3 and 1, respectively. The pressure difference between areas 1 and 3 provides the driving force (i.e. $P_d$) required for the water in the aquifer to flow into area 3. Therefore, the relationship between $P$, $P_b$, and $P_d$ can be expressed as

$$P_d = P - P_b.$$
3.2. Relationship between $H$ and $P_b'$

From the profile, the aquiclude can be regarded as a fixed beam with a uniform load of $Z$ (Figure 5). We label the thickness, span length, gravity density, elastic modulus, sectional moment of inertia, and self-weight uniform load as $H$, $L$, $\gamma$, $E$, $I$, and $G$, respectively. The beam is subjected to a vertical downward load of $G$ and a vertical upward load of $P_b$ (Figure 5). In the event of water inrush, the aquifer can be broken by hydraulic pressure; thus, $P_b$ is actually greater than $G$. Then, we can state that

$$Z = P_b - G,$$  

$$G = \gamma H.$$  

Aquicludes are mostly formed by mudstone and sandy mudstone, which have an average $\gamma$ of 20 kN/m$^3$. When $\gamma$ and $H$ are multiplied directly, the unit of $G$ is kPa. As the unit of water pressure is MPa, the unit of $G$ should be converted to MPa to align all units of pressure. Thus, $\gamma = 0.02$ MN/m$^3$. Then Equations (2) and (3) can be combined to give

$$Z = P_b - \gamma H = P_b - 0.02H.$$  

The maximum tensile stress ($\sigma_{\text{max}}$) occurs at the position of the maximum bending moment ($M_{\text{max}}$), with

$$\sigma_{\text{max}} = \frac{6M_{\text{max}}}{H^2},$$  

where $M_{\text{max}}$ is the bending moment of the fixed beam at its ends (Figure 5(b)). Here,

$$M_{\text{max}} = \frac{ZL^2}{12}.$$  

Figure 5. Calculation model of a fixed beam. Distribution characteristics of (a) load exerted on the fixed beam, (b) bending moment of the fixed beam, and (c) deflection of the fixed beam.
Equations (5) and (6) can then be combined to give

$$Z = \frac{2H^2\sigma_{\text{max}}}{L^2},$$

and Equations (4) and (7) can be combined to give

$$P_b = \frac{2\sigma_{\text{max}}}{L^2} \cdot H^2 + 0.02H.$$ (8)

Assuming that the tensile strength of the fixed beam is $\sigma_s$, $\sigma_{\text{max}} = \sigma_s$ occurs and $P_b$ reaches its maximum value of $P'_b$ when the aquiclude reaches its critical breaking state. Therefore, when the aquiclude reaches its critical breaking state, Equation (8) can be rewritten as follows:

$$P'_b = \frac{2\sigma_s}{L^2} \cdot H^2 + 0.02H.$$ (9)

Each mine in the same coal field (viz., the North China coal field in this study) exhibits only small differences in $\sigma_s$ and $L$. Therefore, the fraction in Equation (9) can be regarded as a constant, $C_1$. Hence, we obtain

$$P'_b = C_1 \cdot H^2 + 0.02H.$$ (10)

To accurately determine the relationship between $H$ and $P'_b$, data from 150 water-inrush points for the North China coal field were used for statistical analysis in this study (Figure 6). This sample comprised of 75 small water-inrush points (amount of gushing water ($Q \leq 60$ m$^3$/h) and 75 large water-inrush points ($Q > 60$ m$^3$/h). Figure 6 is a $P$–$H$ plot of these data points.

As discussed earlier, water inrush occurs when $P > P'_b$. As shown in Figure 6, for a given $H$, the value of $P'_b$ should be in the area where the value of $P$ is relatively small. Considering the expression for $P'_b$ in Equation (10), and to ensure that the $P$ values of most water-inrush points were larger than the corresponding $P'_b$ values, points A (0, 0), B (20, 0.68), and C (40, 1.92) were selected as control points for polynomial interpolation. Then, the following equation was derived to describe the relationship between $H$ and $P'_b$:

$$P'_b = 0.0007H^2 + 0.02H.$$ (11)

Figure 6. Plot of $P$ against $H$. Selection of control points and curve fitting of $H$–$P'_b$. 
Thus, the \( H-P_b' \) curve was obtained using Equation (11). As shown in Figure 6, most water-inrush points were in the region above the \( H-P_b' \) curve. In addition, the \( H-P_b' \) curve was as close as possible to the region in which the values of \( P \) were relatively small. Thus, it is appropriate to use Equation (11) to describe the relationship between \( H \) and \( P_b' \).

### 3.3. Relationship between \( q \) and \( P_d \)

#### 3.3.1. Relationship between \( D \) and \( P_d \)

We next describe the water seepage process from areas ① to ③ in Figure 3. Many interrelated and constantly varying factors influence the process of aquiclude deformation such as the deflection (\( y \)) of the fixed beam, the volume (\( V \)) of the cavity, and the hydraulic gradient (\( J \)) in the seepage process. In addition, \( P_b \) and \( P_d \) are constantly changing at different times. At time \( t \), we label the cavity volume \( V_t \), the hydraulic gradient in the seepage process \( J_t \), the \( P_b \) acting on the aquiclude \( P_{bt} \), and the \( P_d \) between areas ① and ③ \( P_{dt} \). After a very short time interval (\( dt \)), the volume newly added to the cavity is \( dV \), which is caused by the flow and filling of water from the aquifer into the cavity. Thus, \( dV \) is also equal to the volume of water flowing into the cavity within \( dt \). As noted above, the transmissibility coefficient of the aquifer is \( D \); hence,

\[
dV = D \cdot J_t \cdot dt.
\]  

(12)

If the length of the seepage path between areas ① and ③ is labelled \( l \), Equation (12) can be transformed into the following equation:

\[
dV = D \cdot \frac{h_t}{l} \cdot dt,
\]  

(13)

where \( h_t \) is the difference in the water head height between areas ① and ③ at time \( t \). When the unit of \( P_{dt} \) is MPa and the unit of \( h_t \) is m, we obtain

\[
h_t = 100P_{dt}.
\]  

(14)

Equations (13) and (14) can then be combined to give

\[
dV = 100 \frac{D}{l} P_{dt} \cdot dt.
\]  

(15)

From Eq. (15), it is apparent that \( D \) and \( P_{dt} \) are inversely proportional when \( dV \) and \( dt \) are unchanged and for a certain \( l \). When \( dt \) expands to \( t_o \), only a small \( P_{dt} \) can ensure that cavity will be filled and that \( P_b \) will be transmitted continuously within \( t_o \) if \( D \) is large, whereas a larger \( P_{dt} \) is required if \( D \) is small. Therefore, if the actual \( D \) of the aquifer is too small to ensure that \( P_b \) is continuously transmitted, the aquiclude will not be destroyed and water inrush will not occur.

#### 3.3.2. Relationship between \( q \) and \( D \)

The water richness of aquifers is often described in terms of the specific yield (\( q \)), which refers to the sustainable water yield from a drill hole with a diameter of 91 mm when water levels drop by 1 m within the unit time during a pumping test. The unit of \( q \) is usually L/(s·m). Since the units of \( D \) and \( q \) are m²/d and L/(s·m), respectively, the physical meaning of the unit of \( D \) is actually the same as the physical meaning of the unit of \( q \). In order to facilitate the comparison between \( D \) and \( q \), the unit of \( D \) was converted to L/(s·m) in this paper. Wang (1984) and Ge (1984) have both reported a linear positive correlation between \( q \) and \( D \) (Figure 7), which can be expressed as

\[
D = 1.1443q.
\]  

(16)
3.3.3. Relationship between $q$ and $P_d$

Following the analysis in Sections 3.3.1. and 3.3.2., it is easy to determine the relationship between $q$ and $P_d$. Equations (15) and (16) can be combined to obtain

$$dV = 114.43 \frac{q \cdot P_{dt}}{l} \cdot dt.$$

Equation (17) indicates that when $dV$ and $dt$ are unchanged, $q$ and $P_{dt}$ are inversely proportional for a certain $l$. When $dt$ expands to $t_a$, we can conclude that only a small $P_d$ can ensure that the cavity will be filled and that $P_b$ will be transmitted continuously within $t_a$ if $q$ is large, whereas the required $P_d$ is larger if $q$ is small. Therefore, if the actual $q$ of the aquifer is too small to ensure that $P_b$ is continuously transmitted, the aquiclude will not be destroyed and water inrush will not occur. Thus, $q$ is also an important factor affecting the occurrence of water inrush.

3.4. Relationship between $P$, $H$, $q$, and $t_r$

3.4.1. Relationship between deflection and cavity volume

Usually, when the mechanics of a beam are analysed, the default value of the beam width is the unit width. As shown in Figure 5(c), the area surrounded by the deflection curve and x-axis can be considered as corresponding to $V$ when the fixed-beam width is the unit width. As shown in Figure 5(c), the largest deflection occurs at the beam’s centre; below, this deflection is used to calculate $V$. The deflection at the centre of the rock beam is labelled $y$ in this paper. Unless otherwise stated, the deflection referred as follows is that at the centre of the beam only.

At time $t$, the $P_b$ that acts directly on the fixed beam is $P_{bt}$, the $P_d$ between areas (1) and (3) is $P_{dt}$, the sum of each load acting on the fixed beam is $Z_r$, the deflection is $y_r$, and the volume of the cavity is $V_r$. For a certain span length ($L$) of the aquiclude,

$$y_r = \frac{Z_r L^4}{384EI}.$$
Equations (18) and (19) can then be combined to give

\[ V_t = \frac{384}{720} L \cdot y_t = \frac{8}{15} L \cdot y_t. \]  

(20)

It is apparent from Equation (20) that, for the constant \( L \), \( V_t \) is linearly positive with \( y_t \).

3.4.2. Calculation of \( t_r \)

After \( dt \), the volume newly added to the cavity is \( dV \) and the newly added deflection is \( dy \) (Figure 8).

With reference to Equation (20), \( dV \) can be calculated from

\[ dV = V_{(t+dt)} - V_t = \frac{8}{15} L \cdot [y_{(t+dt)} - y_t] = \frac{8}{15} L \cdot dy. \]  

(21)

Equations (1), (17), and (21) can be combined to give

\[ \frac{8}{15} L \cdot dy = 114.43 \cdot \frac{q \cdot (P - P_{bt})}{l} \cdot dt. \]  

(22)

Further, from Equation (4)

\[ P_{bt} = Z_t + \gamma H = Z_t + 0.02H, \]  

(23)

and from Equation (18)

\[ Z_t = \frac{384EI}{L^4} \cdot y_t. \]  

(24)

Equations (22)–(24) can be combined to give

\[ \frac{8}{15} L \cdot dy = 114.43 \cdot \frac{q \cdot (P - 0.02H - \frac{384EI}{L^4} \cdot y_t)}{l} \cdot dt. \]  

(25)

Equation (25) can then be converted to the following form:

\[ dt = \frac{0.00466E \cdot L}{q} \cdot \frac{1}{\left[(P - 0.02H - \frac{384EI}{L^4} \cdot y_t)\right]} \cdot dy. \]  

(26)

Figure 8. Diagrammatic sketch of newly added volume (i.e. area filled with blue cyan) and deflection within \( dt \).
Taking the integral of both sides of Equation (26), we obtain

\[
\int_0^{t_r} dt = \frac{0.00466L \cdot l}{q} \cdot \int_0^{y_{\text{max}}} \frac{1}{\left[\left(P - 0.02H\right) - \frac{384EI}{L^4} \cdot y\right]} dy,
\]

(27)

where \(y_{\text{max}}\) refers to the maximum deflection that can eventually be achieved during beam bending, or the deflection of the beam when it reaches critical breaking state.

From Equation (27), we obtain

\[
t_r = 1.21 \times 10^{-5} \frac{L^5l}{qEI} \cdot \ln\left\{ \frac{P - 0.02H}{\left(P - 0.02H\right) - \frac{384EI}{L^4} \cdot y_{\text{max}}} \right\}.
\]

(28)

Then, from Equations (4) and (18), we find

\[
y_{\text{max}} = \frac{L^4}{384EI} \cdot Z_{\text{max}} = \frac{L^4}{384EI} \left(P_{\text{bmax}} - 0.02H\right),
\]

(29)

where \(P_{\text{bmax}}\) refers to the maximum value of \(P_b\). Obviously, \(P_{\text{bmax}} = P_b'\) occurs when the aquiclude reaches its critical breaking state. Then, Equation (29) can be converted to

\[
y_{\text{max}} = \frac{L^4}{384EI} \left(P_b' - 0.02H\right).
\]

(30)

Equations (28) and (30) can be combined to give

\[
t_r = 1.21 \times 10^{-5} \frac{L^5l}{qEI} \cdot \ln\left( \frac{P - 0.02H}{P - P_b'} \right),
\]

(31)

and Equations (11) and (31) can be combined to give

\[
t_r = 1.21 \times 10^{-5} \frac{L^5l}{qEI} \cdot \ln\left( \frac{P - 0.02H}{P - 0.0007H^2 - 0.02H} \right).
\]

(32)

Because the fixed-beam cross-section is rectangular, the moment of inertia \(I\) of the cross-section can be expressed as

\[
I = \frac{H^3}{12}.
\]

(33)

Finally, Equations (32) and (33) can be combined to give

\[
t_r = 1.45 \times 10^{-4} \frac{L^5l}{E} \cdot \frac{1}{qH^3} \cdot \ln\left( \frac{P - 0.02H}{P - 0.0007H^2 - 0.02H} \right).
\]

(34)

There is little variation between the \(L, l,\) and \(E\) of the aquicludes in each mine in the same coal field (i.e. the North China coal field in this study). Therefore, the fraction featuring these terms in Equation (34) can be regarded as a constant, here labelled \(C_2\). Then, Equation (34) becomes

\[
t_r = C_2 \cdot \frac{1}{qH^3} \cdot \ln\left( \frac{P - 0.02H}{P - 0.0007H^2 - 0.02H} \right).
\]

(35)

Thus, an expression indicating the relationship between \(P, H, q,\) and \(t_r\) is obtained.
4. Analysis of role of $P$, $H$, and $q$ in water-inrush occurrence based on time-related function

Water-inrush data from 135 cases were collected from the Feicheng, Jiaozuo, and Zibo mining areas of the North China coal field (Figure 4). These data were systematically analysed and used as the basis for the $P$-$H$-$q$ evaluation system proposed later.

4.1. Time-related function to evaluate the likelihood of water inrush

The aquiclude can only be destroyed and water inrush can only occur within $t_a$ when $t_r < t_a$. Therefore, referring to Equation (35), all water inrush points must satisfy the following inequality:

$$t_r = C_2 \cdot \frac{1}{qH^3} \cdot \ln \left( \frac{P - 0.02H}{P - 0.0007H^2 - 0.02H} \right) < t_a.$$  \hspace{1cm} (36)

Inequality (36) can be converted to the following form:

$$\frac{1}{qH^3} \cdot \ln \left( \frac{P - 0.02H}{P - 0.0007H^2 - 0.02H} \right) < \frac{t_a}{C_2},$$  \hspace{1cm} (37)

where we define the left side of this inequality as the time-related function $f(P, H, q)$. That is,

$$f(P, H, q) = \frac{1}{qH^3} \cdot \ln \left( \frac{P - 0.02H}{P - 0.0007H^2 - 0.02H} \right).$$  \hspace{1cm} (38)

To ensure that all water-inrush points satisfy inequality (37), we set the maximum value of the time-related function, $f(P, H, q)_{\text{max}}$ as follows:

$$\frac{t_a}{C_2} = f(P, H, q)_{\text{max}}.$$  \hspace{1cm} (39)

In Figures 9(a–c), the values of $f(P, H, q)$ calculated using the data from the 135 water-inrush points are plotted against $P$, $H$, and $q$, respectively. Hence, we obtain $f(P, H, q)_{\text{max}} = 4.30 \times 10^{-4}$ when the units of $P$, $H$, and $q$ are MPa, m, and L/(s·m), respectively.

Thus, inequality (37) can be converted to the following form:

$$\frac{1}{qH^3} \cdot \ln \left( \frac{P - 0.02H}{P - 0.0007H^2 - 0.02H} \right) < 4.30 \times 10^{-4}.$$  \hspace{1cm} (40)

For a mining face with $P$, $H$, and $q$ satisfying inequality (40), water inrush will occur during future mining processes.

4.2. Role of $P$, $H$, and $q$ in occurrence of water inrush from a coal seam floor

From the above analysis, it is apparent that the likelihood of water inrush decreases with increased $f(P, H, q)$. Further, water inrush will not occur when $f(P, H, q)$ increases to more than $4.30 \times 10^{-4}$. Thus, the greater the value of $f(P, H, q)$, the safer the mining face. The effects of $P$, $H$, and $q$ on the value of $f(P, H, q)$ were analysed based on the plots shown in Figure 10.
Figure 9. Scatter plots of $f(P, H, q)$ against $P$, $H$, and $q$, for all 135 water-inrush points collected in North China coal field.
Figure 10. $f(P, H, q)-H$ scatter plots for (a) $q = 0.05 \text{ L/(m·s)}$ with smooth lines under different $P$, and (b) $P = 7 \text{ MPa}$ with smooth lines under different $q$. 
As shown in Figure 10, in the vertical direction, the value of \( f(P, H, q) \) decreases with increased \( P \) and \( q \). This phenomenon shows that both \( P \) and \( q \) play an important role in the occurrence of water inrush. Specifically, the likelihood of water inrush increases with increased \( P \) and \( q \).

In the horizontal direction, the value of \( f(P, H, q) \) first decreases with increased \( H \) and then increases. This phenomenon occurs because, on the one hand, the increase of \( H \) reduces \( V \), thereby reducing the amount of water to be transported. On the other hand, \( P_b \) increases (for details, see Equation 8) and causes a reduction in \( P_d \) (see Equation 1). When the reduction of \( V \) equals the degree of \( P_d \) reduction, the corresponding \( H \) is the turning point thickness \( (H_t) \). Figure 10(a) shows that \( H_t \) increases with \( P \), whereas Figure 10(b) shows that \( H_t \) is independent of \( q \). When \( H \) is less than \( H_t \), the reduction of \( V \) is greater than that of \( P_d \), and the value of \( f(P, H, q) \) decreases with increased \( H \). Conversely, when \( H \) is larger than \( H_t \), the reduction of \( V \) is less than the degree of \( P_d \) reduction, and the value of \( f(P, H, q) \) increases with \( H \). Thus, the likelihood of water inrush increases with increased \( H \) when \( H < H_t \), and decreases with increased \( H \) when \( H > H_t \).

It is important to note that the above analysis operates exclusively under the premise that \( P > P_b' \). If \( P \leq P_b' \), the rock strata will not reach its critical breaking state and water inrush will not occur. Further, if \( P \leq P_b' \), as \( H \) increases, it is increasingly difficult to damage the aquiclude, and the likelihood of water inrush decreases.

| Magnitude of \( q \) | Small water inrush (\( Q \leq 60 \text{ m}^3/\text{h} \)) | Large water inrush (\( Q > 60 \text{ m}^3/\text{h} \)) |
|---------------------|-------------------------------------------------|-------------------------------------|
| \( 0 < q \leq 1.75 \text{ L/s.m} \)       | \( 67 \)                                      | \( 1 \)                               |
| \( q > 1.75 \text{ L/s.m} \)                            | \( 0 \)                                      | \( 67 \)                              |

![Figure 11](image-url) Demarcation line (in green) between different distribution areas of small and large water-inrush points.
5. Establishment and application of the P-H-q evaluation system

5.1. Establishment of the P-H-q evaluation system

5.1.1. Classification of water-inrush risk level based on q

Examining the three graphs in Figure 9, an obvious demarcation line between the distribution area of the large and small water-inrush points is apparent in Figure 9 (c). This shows that q plays an important role in the amount of gushing water (Q).

Table 1 shows the categorization of the 135 water-inrush points with different Q in response to different magnitudes of q. Of the 135 water-inrush cases, 67 and 68 exhibited small (≤60 m³/h) and large Q (>60 m³/h), respectively. From Table 1, it is apparent that all small Q points and only one large Q point were located in the area with q < 1.75 L/(s·m). The remaining large Q points were all located in the area for which q > 1.75 L/(s·m). Thus, we can draw a demarcation line of q = 1.75 L/(s·m) between the distribution areas of the small and large Q points (the green line in Figure 11).

\[
\text{If } P \leq P'_b \quad \text{and} \quad f(P, H, q) \geq 4.30 \times 10^{-4} \quad \rightarrow \text{Safe}
\]
\[
\text{If } P > P'_b \quad \text{and} \quad f(P, H, q) < 4.30 \times 10^{-4} \text{ and } \{ q < 1.75 \text{ L/(s·m)} \} \quad \rightarrow \text{Risk}
\]
\[
\text{If } P > P'_b \quad \text{and} \quad f(P, H, q) < 4.30 \times 10^{-4} \text{ and } \{ q \geq 1.75 \text{ L/(s·m)} \} \quad \rightarrow \text{High Risk}
\]

\[
P'_b = 0.0007H^2 + 0.02H
\]
\[
f(P, H, q) = \frac{P - 0.02H}{qH^3} \cdot \ln \left( \frac{P - 0.0007H^2 - 0.02H}{P - 0.0007H^2 - 0.02H} \right)
\]

P: aquifer water pressure, MPa; H: aquifuge thickness, m; q: aquifer specific yield, L/(s·m); P'_b: critical pressure of aquifuge breaking, MPa; f(P, H, q): time-related function

Figure 12. Discrimination diagram for risk level of water inrush from coal seam floor under premise of \( P > P'_b \).

Figure 13. P-H-q evaluation system used to evaluate likelihood of water inrush.
Table 2. Evaluation results of risk of floor water inrush at eight mining faces in the North China coal field.

| Mining face                  | P (MPa) | H (m) | Q (L/s.m) | T (MPa/m) | \( P_b' \) (MPa) | \( f(P, H, q) \) \( \times 10^{-6} \) | T method (MPa/m) | \( P-H-q \) evaluation system (\( \times 10^{-4} \)) | Evaluation results | Ground-truth verification |
|------------------------------|---------|-------|-----------|-----------|------------------|---------------------------------|------------------|------------------------------------------------|-------------------|--------------------------|
| 1023, Taoyuan II mine        | 4.785   | 55    | 0.002     | 0.087     | 3.22             | 25.68                           | 0.07             | 4.30                                           | Risky             | Safe                     | Safe                |
| 1024, Taoyuan II mine        | 4.015   | 55    | 0.016     | 0.073     | 3.22             | 4.87                            | 0.07             | 4.30                                           | Risky             | Safe                     | Safe                |
| 10414, Yangliu mine          | 7.26    | 110   | 0.001     | 0.066     | 10.67            | –                               | 0.07             | 4.30                                           | Safe              | Safe                     | Safe                |
| 1034, Zhuxianzhuang II mine  | 5.022   | 62    | 0.012     | 0.081     | 3.93             | 4.35                            | 0.07             | 4.30                                           | Risky             | Safe                     | Safe                |
| 1021, Yuandian I mine        | 4.214   | 49    | 0.013     | 0.086     | 2.66             | 4.76                            | 0.07             | 4.30                                           | Risky             | Safe                     | Safe                |
| 1036, Zhuxianzhuang II mine  | 6.285   | 83.8  | 0.013     | 0.075     | 6.59             | –                               | 0.07             | 4.30                                           | Risky             | Safe                     | Safe                |
| 1044, Liudian mine           | 6.93    | 33    | 0.006     | 0.210     | 1.42             | 6.01                            | 0.07             | 4.30                                           | Risky             | Safe                     | Safe                |
| 1037, Liudian mine           | 6.6     | 20    | 0.012     | 0.330     | 0.68             | 4.81                            | 0.07             | 4.30                                           | Risky             | Safe                     | Safe                |

\( P_b' \) indicates that \( P < P_b' \) occurs here, meaning that no water inrush will occur at this mining face at this time.
We then subdivided the area for which \( f(P, H, q) < 4.30 \times 10^{-4} \). The distribution areas of the small and large Q points were labelled the ‘risk zone’ and ‘high-risk zone’, respectively. The area for which \( f(P, H, q) \geq 4.30 \times 10^{-4} \) was named the ‘safe zone’. Thus, we obtained the discrimination diagram shown in Figure 12 under the premise of \( P > P'_b \). The risk level of water inrush from the coal seam floor can be determined easily once the \( q \) and \( f(P, H, q) \) values for a mining face are compared to Figure 12.

It is important to reiterate that the above result was obtained under the premise of \( P > P'_b \). Again, if \( P \leq P'_b \), the rock strata will not reach its critical breaking state and water inrush will not occur; thus, inequality (40) is not needed to determine the likelihood of water inrush in such cases.

5.1.2. P-H-q evaluation system

Based on Figure 12 and incorporating the case where \( P \leq P'_b \), the P-H-q evaluation system is thus proposed, as outlined in Figure 13.

5.2. Application

Table 2 presents data for eight coal mines in North China coal field, along with results obtained using the P-H-q evaluation system to evaluate the risk of floor water inrush for those eight mining faces. Evaluation results from the traditional method are also shown in Table 2, for comparison.

We used the prescriptive water-inrush coefficient threshold (\( T_S \)) of 0.07 MPa/m, currently used for these mines. Thus, based on the data in Table 2, seven of the eight mining faces have \( T \) values greater than \( T_S \), with only the 10414 mining face of Yangliu mine having a \( T \) value lower than \( T_S \). In summary, seven of the eight mining faces were evaluated as having a floor water-inrush risk, according to the \( T \) method. However, the opposite conclusion was obtained using our P-H-q evaluation system. That is, based on the evaluation results yielded by the P-H-q evaluation system, these seven mining faces are all safe for exploitation. In fact, all eight mining faces have been mined, and no water inrush accidents occurred, cumulatively producing 3.44 million tons of raw coal. These ground-truth data from the North China coal field clearly demonstrate that the P-H-q evaluation system is suitable for practical application.

6. Conclusions

This study developed a P-H-q evaluation system to determine the risk of floor water inrush for coal mines based on data from the North China coal field. The findings of this study can be summarized as follows:

(1) Mining data collected at 150 mining faces in four mining areas of the North China coal field demonstrate a positive correlation between \( H \) and \( P'_b \).
(2) A time-related function, \( f(P, H, q) \), was developed to evaluate the likelihood of water inrush based on rock-breaking theory and water-pressure transmission theory. It was found that the likelihood of water inrush decreases with increased \( f(P, H, q) \). Water inrush will not occur in a mining face when the value of \( f(P, H, q) \) increases to more than \( 4.30 \times 10^{-4} \).
(3) The likelihood of water inrush increases with increased \( P \) and \( q \) at any time, and decreases with increased \( H \) when \( H > H_t \).
(4) The P-H-q evaluation system considers a greater number of hydrogeological factors than the currently employed \( T \) method, and also clarifies the roles of these factors in the occurrence of water inrush, thereby elucidating the mechanism of water inrush from a coal seam floor.
research results will also provide a reference for evaluating the risk of water inrush in other coal fields.

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