Risk assessment of water inrushes from bed separations in Cretaceous strata corresponding to different excavation lengths during mining in the Ordos Basin

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ABSTRACT

Evaluation of the risk of bed-separation water inrush (BWI) hazards in Cretaceous strata is required for safe mining in the Ordos Basin, China. In this paper, three coal mines in the Ordos Basin were selected for detailed evaluation of the water inrush risk. The multifactor superposition method and stress balance arch theory were used to obtain the water inrush risk in the mines from bed separations at different excavation lengths. First, the related BWI factors were analyzed, and the BWI risk index at any coordinate point in the study area was calculated using multifactor superposition. The weights of relevant factors were obtained using the entropy weight method. Then, based on stress arch theory, the overall BWI risk index in the bed-separation zone corresponding to any excavation length was calculated. Finally, the boundary values between different risk levels were obtained by comparing the overall risk in the mining area with and without BWIs. With the help of these boundary values, the overall BWI risk in bed-separation zones corresponding to any excavation length in some mining areas was evaluated. The evaluation results were verified in practice, which demonstrated the scientific basis for and practicality of this BWI risk assessment method.

1. Introduction

Coal accounts for a large proportion of China’s energy production and consumption, and the Ordos Basin has become the main coal producing area in China (Liu et al. 2018; Liu and Li 2019). A bed separation is a kind of horizontal fracture caused by the asynchronous settlement of adjacent strata in overburden during coal mining (Palchik 2003; 2005; Peng 2006; Xu et al. 2012). When water accumulates in bed separation, it is called bed-separation water. When bed-separation water suddenly bursts into the mining area due to an overburden fracture, a bed-separation water inrush...
(BWI) occurs (Gui and Lin 2016). Because China has the largest scale of coal mining in the world and has the most complex geological conditions for coal mining, almost all the existing records of BWI accidents are concentrated in China. BWI accidents have been both unpredictable and extremely destructive. For example, in 2005, five people died in a BWI accident in the Haizi mine, China, and in 2016, 11 people died in a BWI accident in the Zhaojin mine, China (Li et al. 2018). As coal mining in the Ordos Basin gradually transitions to the central part of the basin, which has geology that is favorable for forming BWIs, it is necessary to evaluate the risk of BWIs before mining.

At present, there are few research results on BWIs and BWI risk assessments. Some research has obtained the distribution area of bed separations by examining roof strata deformation and failure behavior (Xuan and Xu 2014; Rezaei et al. 2015; Meng et al. 2016; Wang et al. 2016; 2017; Yan et al. 2016; Cheng et al. 2017; Wang and Li 2017; Huang et al. 2018; Ma et al. 2019; Yin et al. 2019), which is helpful for preventing and controlling BWIs because bed separations in distribution areas with high voidage accumulate more roof water. Gui et al. (2018; 2019) believed that in a BWI risk assessment, the bed separations in the lower part of the bending zone in the overburden should be the focus. He et al. (2018; 2020) and He et al. (2018) simplified the representation of the deformation and breakage area of overlying rock to a triangular overburden deformation area (TODA). Bed-separation water can only be distributed in a TODA, and those bed separations correspond to different excavation lengths, which are then the focus of a BWI risk assessment. Palchik (2010; 2020) found that horizontal fracture apertures (i.e., the openings of bed separation) were 0.03-0.29 times the mining thickness, which is helpful to more accurately evaluate the water inflow scale when BWIs occur. After analyzing the cause of the BWI in the Haizi mine, China, Li (2011) found that the impact of the fracture in the stratum above the bed separation was the factor that most influenced the BWI. In the Yangliu mine, Li et al. (2018) found that overlying strata damage above bed separation induced the BWI. Other scholars also studied the water and gas outburst accident in the Yangliu mine and concluded that the mixture of water and gas came from the bed separation under igneous rock that was induced by the fracturing and influence of the igneous rock (Xu et al. 2014; Shu et al. 2015; Wu et al. 2018; Zhang et al. 2020). After analyzing the cause of the BWI accidents in the Cuimu mine, China, Fan et al. (2019a) found that Cretaceous bed-separation water was the source of water in the BWI and that evaluating the stability of the aquiclude was the key to accurately assessing BWI risk. However, the role of the fractured aquiclude in BWIs was ignored, although it had the ability to resist water due to closure of the fracture. Fan et al. (2019b) established a BWI mechanical model and deduced the theoretical discriminant of the first and periodic BWIs. However, the driving force of BWIs was found to be bed-separation water pressure, which was inconsistent with other results that suggested that the driving force was derived from the fracture and impact of the rock strata above the bed separation. There is no unified view on the formation mechanism of BWIs, and identifying the main force driving the induction of BWIs is also contested. The multifactor superposition method is a trusted risk assessment method and is often used in mine roof/floor water inrush risk assessments. For
example, Lu et al. (2018) and Lu (2019) chose five risk factors to test: hard rock thickness, coal seam thickness, aquifuge thickness, aquifer thickness, and hydrostatic head. However, because the boundary values between different risk levels were obtained by a natural classification method in ArcGIS, the boundary values changed with the mining area range and number of points that were sampled, which was not a realistic assumption. By using the water inrush coefficient method, Fan et al. (2019b) obtained the boundary values between different BWI risk levels in the Shilawusu mine. However, the formula determining the water inrush coefficient is an empirical formula based on a large number of floor water inrush cases, which is unsuitable for the assessment of BWI risk due to its association with roof water inrush. Therefore, there is still a lack of a BWI risk assessment method that adheres to scientific assessment principles and provides reasonable and realistic risk classification in the research field of BWIs.

The multifactor superposition method is still an appropriate scientific risk assessment method if it can provide practical boundary values. One solution is to combine

![Figure 1. Thickness of Cretaceous strata and distribution of the study areas in the Ordos Basin.](image)
multifactor superposition with scientific risk division. In addition, because the occurrence of BWIs is induced by the breaking of rock layers that require a certain length, it is meaningless to obtain the risk at a certain point and more meaningful to obtain the overall risk in a specific bed-separation zone. To better understand and address these issues, the objective of this paper was to obtain the overall risk index of BWIs in a bed-separation zone corresponding to different excavation lengths and to define the boundary values between different risk levels.

2. Research site background

2.1. Engineering and geological conditions relevant to coal mining in the Ordos Basin

Jurassic coal seam mining in the Shaanxi and Inner Mongolia energy bases in the Ordos Basin has become the main supplier for China’s coal production, producing 1.71 billion tons in 2020 (accounting for 43% of the national annual production). The production capacity is projected to continue to increase in 2021. With the end of shallow coal seam mining at the edge of the basin, the deep coal seam in the middle of the basin has become the focus of both present and future mining. Due to the thick Cretaceous strata deposited in the middle of the Ordos Basin (Figure 1), the presence of a Cretaceous aquifer with high water yield properties poses a threat to mining operations below it. For example, Cretaceous BWIs have occurred in the Cuimu, Shilawusu, Yuhua, and Zhaojin mines in the Ordos Basin.

The Cretaceous strata in the study area have an average thickness of 350 m (Figure 1). The lithologies are mainly medium and fine sandstone with minor siltstone and sandy mudstone intercalations (Figures 2 and 3). The Jurassic Anding Formation is mainly composed of siltstone and sandy mudstone (Figure 3) and contains a weathered zone (Figures 4 and 5). In addition, it has a high argillaceous content that easily disintegrates when in contact with water, and the texture is relatively soft (Figure 6).
On the one hand, due to Cretaceous argillaceous intercalations, the strata settled asynchronously due to the difference in deformation during subsidence, resulting in several bed separations. On the other hand, because the Cretaceous strata are integral structures that resist deformation, and the Anding Formation has weathering phenomena, the overall anti-deformation ability of the Cretaceous strata is stronger than

Figure 3. Stratigraphic profile of mining area 106 A in the Shilawusu coal mine.

Figure 4. Outcrop of the interface between Cretaceous strata and the Jurassic Anding Formation in the Ordos Basin (October 2019, Jingbian, China).
that of the Anding Formation, leading to bed separations at their interface during coal mining (Figure 7). In this case study, when bed-separation water burst into the mining site, a BWI occurred.

Figure 5. Rock cores drilled in the Yingpanhao mine of (a) Cretaceous strata and (b) the Jurassic Anding Formation.

Figure 6. Rock cores drilled in the Cuimu mine of (a) Cretaceous strata and (b) the Jurassic Anding Formation.

Figure 7. Schematic diagram of a bed separation in Cretaceous strata formed during mining of the Jurassic coal seam: 1-Flowing-water fracture zone; 2-Jurassic residual protective layer; 3-Bed-separation zone; 4-Overall subsidence zone; i-Sequence number of rock layer; \( o_i \)-Opening degree of bed separation under the \( i \)th layer; \( T_i \)-Total thickness of all strata between the \( i \)th layer and the coal seam.
2.2. Factors related to BWIs

According to He (2018), the process by which BWIs are formed and the related factors in each process are shown in Figure 8.

Figure 8 shows that there are six factors related to BWIs: mining thickness \( M \), average thickness of Cretaceous rock layers in the bed-separation zone \( T_C \), proportion of medium sandstone/coarse sandstone in the Cretaceous strata \( \Phi \), thickness of the Jurassic residual protective layer \( T_J \), self-healing potential of mudstone fractures in the flowing-water fracture zone \( P_m \), and filling potential of sandstone fractures in the flowing-water fracture zone \( P_s \). The role of these related factors in BWIs is as follows.

2.2.1. Mining thickness \( M \)

Coal mining provides subsidence space for overburden rock, which can be calculated using the following equation:

\[
\omega_i = M - (T_i - D_i) \times (\eta - 1),
\]

and when the deformation of the \( i^{th} \) layer is very small,

\[
\omega_i = o_i
\]

where \( \omega_i \) is the height of the available settlement space under the \( i^{th} \) layer; \( M \) is the mining thickness; \( T_i \) is the total thickness of all strata between the \( i^{th} \) layer and the coal seam (Figure 7); \( D_i \) refers to the distance between the top boundary of the flowing-water fracture zone and the \( i^{th} \) layer; \( \eta \) is the average fragmentation coefficient of
the fractured rock mass in the flowing-water fracture zone; and \( o_i \) is the opening degree of bed separation under the \( i^{th} \) layer (Figure 7).

Eqs. (1)-(2) show that \( M \) is positively correlated with \( o_i \). Moreover, larger values of \( o_i \) demonstrate more bed-separation water and a greater BWI risk. Therefore, \( M \) is positively correlated with BWI risk.

2.2.2. Average thickness of Cretaceous rock layers in the bed-separation zone (\( T_C \))

The span of bed separation is determined by the limit span of the rock layer above it before fracturing, and a larger limit span leads to a greater bed separation span. Limit span can be calculated as:

\[
I_{\text{max}} = \sqrt{\frac{2t\sigma_s}{\gamma}},
\]

where \( I_{\text{max}}, t, \gamma, \) and \( \sigma_s \) refer to the limit span, thickness, bulk density, and tensile strength of the rock layer, respectively.

According to Eq. (3), \( I_{\text{max}} \) is positively correlated with \( t \). Therefore, the bed-separation span is positively correlated with the thickness of the strata above it. For Cretaceous bed-separation water, \( T_C \) is positively correlated with the risk of BWIs in Cretaceous strata. Because bed separations are distributed in the stress balance arch (He et al. 2020) (Figure 9), \( T_C \) refers to the average thickness of Cretaceous strata in the stress balance arch.

2.2.3. Proportion of medium sandstone/coarse sandstone in the Cretaceous strata (\( \Phi \))

Because the bed-separation water is from the surrounding aquifer, the water yield properties and permeability of the aquifer affects the efficiency of how the water fills the bed separations. As the water yield properties and permeability of medium sandstone/coarse sandstone are greater than those of siltstone/fine sandstone, greater \( \Phi \) values reflect higher water filling efficiency. Higher filling efficiency results in more bed-separation water and a greater threat to the mining area. Therefore, \( \Phi \) is positively correlated with the risk of BWIs in Cretaceous strata.

Figure 9. Stress balance arches and bed-separations during mining.
2.2.4. Thickness of the Jurassic residual protective layer (TJ)
The residual protective layer refers to Jurassic strata that are not penetrated by the flowing-water fracture zone (Figure 7). TJ is positively correlated with the risk of BWIs in Cretaceous strata.

2.2.5. Self-healing potential of mudstone fractures in a flowing-water fracture zone (Pm)
The water resistance of mudstone in a flowing-water fracture zone is due to the large proportion of mudstone in the Jurassic (Figure 10) and the self-healing effect of mudstone fractures under water flow (Figure 11). Here, Pm was used as an index to evaluate the self-healing effect of mudstone fractures in a flowing-water fracture zone. Pm was negatively correlated with the BWI risk.

Because Pm is positively correlated with the volume of mudstone and the volume of mudstone is positively correlated with its thickness, Pm is positively correlated with mudstone thickness. Rock layer fractures in the stress arch are caused by subsidence, and larger spaces are available for the rock layers to settle, resulting in a higher degree of fragmentation. A larger degree of fracture opening produces smaller Pm values. The height of the available settlement space can be calculated according to Eq. (1).

In summary, Pm is positively correlated with the thickness of mudstone layers and negatively correlated with the available settlement space. Therefore, the value of Pm can be quantified by the following equations:

\[ P_m = \sum_{i=1}^{n} P_{mi}, \]  

\[ p_{mi} = \frac{t_{mi}}{\omega_{mi}} = \frac{t_{mi}}{M - T_{mi} \times (\eta - 1)}, \]

where \( P_m \) refers to the overall self-healing potential of all mudstones in the flowing-water fracture zone; \( M \) refers to the mining thickness; \( \eta \) refers to the average
2.2.6. Filling potential of sandstone fractures in the flowing-water fracture zone ($P_s$)

Jurassic sandstone is weakly cemented and easily disintegrates in water (Figure 12). Both sandstone cuttings from sandstone self-disintegration and mudstone cuttings from the mudstone above the sandstone fill sandstone fractures. Sandstone in the flowing-water fracture zone has water resistance after its fractures are filled. Here, $P_s$ was used as an index to evaluate the filling effect of sandstone fractures in the flowing-water fracture zone. It was negatively correlated with BWI risk.

$P_s$ was positively correlated with sandstone fracture length and negatively correlated with the degree of opening. Sandstone fracture length can be expressed by its thickness, as the fracture formed after tensile failure is basically vertical. The opening degree of sandstone fractures was positively correlated with the available subsidence space. The height of the available settlement space was calculated according to Eq. (1).

$P_s$ was positively correlated with the thickness of the sandstone layer and negatively correlated with the available settlement space. Therefore, the value of $P_s$ can be quantified by the following equations:

$$P_s = \sum_{i=1}^{n} p_{si}, \quad (6)$$

$$p_{si} = \frac{t_{si}}{\omega_{si}} = \frac{t_{si}}{M - T_{si}(\eta - 1)}, \quad (7)$$

where $P_s$ refers to the overall filling potential of all sandstone in the flowing-water fracture zone; $M$ refers to the mining thickness; $\eta$ refers to the average fragmentation coefficient of the fractured rock mass; $T_{si}$ refers to the total thickness of all strata between the $i^{th}$ sandstone layer and the coal seam; and $p_{si}$, $t_{si}$, and $\omega_{si}$ refer to the
3. Methods and materials

Mining areas 201 and 106 A in the Shilawusu mine were selected to obtain the boundary values between different risk levels.

3.1. BWI risk index at each coordinate point

Mining areas 201 and 106 A in the Shilawusu mine are threatened by BWIs. During the actual mining process, a large BWI occurred in mining area 106 A when the excavation length reached 554 m, which experienced a maximum water inflow of 921 m$^3$/h. However, in mining area 201, large BWIs did not occur, and the water inflow did not fluctuate greatly (Figure 13). The weight of each index in the formation of a BWI can be obtained by comparing the difference in each index between mining areas 106 A and 201, which is consistent with the basic principle of the entropy weight method. In this paper, the entropy weight method was used to calculate the weights of the six related factors.

3.1.1. Determination of sampling point locations

To compare the differences in potentially related factors between the two mining areas, it was necessary to ensure that the selected sampling points were distributed in areas where BWIs may have occurred. Figure 13 shows that when the excavation length was 554 m, a large BWI occurred in mining area 106 A, meaning that the sampling points should be distributed across the corresponding stress balance arch at that length. When the excavation length was 550 m, the change in the water inflow in mining area 201 was most likely caused by a small BWI. Therefore, additional sampling points should be distributed in the corresponding stress balance arch at that length.
Because the curved shape of the stress balance arch was too complex to be used in the calculation, it was necessary to simplify the shape. According to existing research results, the shape of the arch was simplified into a triangle, which is called a triangle stress arch (TSA) (Figure 14) (He 2018; He et al. 2020). In a TSA, the two sides are rock fracture lines, and the arch foot ranges from 55 to 65°.

Using the TSA, when the excavation length was 550 m in mining area 201, the distribution of Cretaceous bed-separation water surrounded by the stress balance arch was calculated to be 157.28 m-387.02 m away from the starting line. Therefore, the sampling points in mining area 201 were distributed within this range from the starting line. Similarly, with the help of a TSA, it was determined that the sampling points in mining area 106 A should be distributed 204.12 m-373.36 m away from the starting line. For
each mining area, nine sampling points were arranged, as shown in Figure 15, and BWI-related factors were measured at each sampling site, as shown in Table 1.

3.1.2. Calculation of index weights

The original data matrix obtained from \( m \) evaluation indexes and \( n \) evaluation objects is written as:

\[
X = (x_{ij})_{m \times n} = \begin{pmatrix}
x_{i1} & \cdots & x_{in} \\
\vdots & \ddots & \vdots \\
x_{m1} & \cdots & x_{mn}
\end{pmatrix},
\]

Figure 15. Distribution of sampling point locations and the BWI risk index contours in mining areas 201 and 106A in the Shilawusu coal mine.
and after standardization, it becomes:

\[ R = (r_{ij})_{m \times n} = \begin{pmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mn} \end{pmatrix}, \]  

(9)

where \( r_{ij} \) is the standard value of the \( j^{th} \) evaluation object for the \( i^{th} \) evaluation index. For the positive correlation index, the formula for \( r_{ij} \) is:

\[ r_{ij} = \frac{x_{ij} - \min_j x_{ij}}{\max_j x_{ij} - \min_j x_{ij}}, \]  

(10)

whereas for the negative correlation index, the formula is:

\[ r_{ij} = \frac{\max_j x_{ij} - x_{ij}}{\max_j x_{ij} - \min_j x_{ij}}. \]  

(11)

Table 1 contains six evaluation indexes, each of which has 18 evaluation objects. The data in Table 1 were standardized, and the results are shown in Table 2.

When there are \( m \) indexes and \( n \) objects to be evaluated, the information entropy \( e_i \) of the \( i^{th} \) index is defined as:

\[ e_i = -\frac{1}{\ln n} \sum_{j=1}^{n} p_{ij} \cdot \ln p_{ij}, \]  

(12)

where the formula of \( p_{ij} \) is:
According to Figure 16, \( p_{ij}/C3\ln p_{ij}=0 \) when \( p_{ij}=0 \).

The information entropy of the six BWI-related factors can be calculated by Eqs. (12)-(13) (Table 3).

After the information entropy of the \( i \)th index is determined, the entropy weight \( u_i \) of the \( i \)th index can be obtained by Eq. (14).

### Table 2. Standardization of BWI-related factors at each sampling site.

| j | 1     | 2     | 3     | 4     | 5     | 6     |
|---|-------|-------|-------|-------|-------|-------|
| 1 | 0.0352| 0     | 0.2959| 0.1408| 0.8625| 0.0847|
| 2 | 0.0439| 0.1973| 0.1518| 0.1884| 0.7946| 0.1855|
| 3 | 0.0285| 0.4393| 0.1686| 0.0775| 0.7151| 0.3743|
| 4 | 0.0324| 0.2983| 0.3087| 0.0848| 0.8127| 0.3403|
| 5 | 0.0282| 0.3663| 0.1343| 0.1084| 0.8226| 0.4823|
| 6 | 0.0167| 0.7065| 0.1008| 0.0418| 0.8349| 0.6666|
| 7 | 0.0272| 0.6538| 0.2846| 0.0247| 0.7675| 0.6257|
| 8 | 0.0111| 0.9800| 0.0653| 0.0397| 0.8609| 0.7909|
| 9 | 0     | 1     | 0     | 0     | 1     | 1     |
| 10| 0.9737| 0.7546| 1     | 0.8529| 0.0605| 0.1374|
| 11| 0.9718| 0.8103| 0.8159| 0.8175| 0.0271| 0.1935|
| 12| 0.9722| 0.7604| 0.6198| 0.7759| 0     | 0.2435|
| 13| 0.9881| 0.6975| 0.9709| 0.9253| 0.1206| 0.0716|
| 14| 0.9868| 0.7556| 0.8132| 0.8699| 0.0842| 0.1190|
| 15| 0.9865| 0.6830| 0.6029| 0.8143| 0.0656| 0.1513|
| 16| 1     | 0.6273| 0.8962| 1     | 0.1834| 0     |
| 17| 0.9989| 0.7089| 0.7728| 0.9212| 0.1378| 0.0435|
| 18| 0.9991| 0.6383| 0.5743| 0.8501| 0.1210| 0.0666|

### Table 3. Information entropy for the six BWI-related factors.

| e1 | e2  | e3  | e4  | e5  | e6  |
|----|-----|-----|-----|-----|-----|
| 1.0504 | 1.2626 | 1.1864 | 1.1177 | 1.1328 | 1.1361 |

\[
 p_{ij} = \frac{r_{ij}}{\sum_{j=1}^{n} r_{ij}}. \tag{13}
\]

According to Figure 16, \( p_{ij}/C3\ln p_{ij}=0 \) when \( p_{ij}=0 \).

The information entropy of the six BWI-related factors can be calculated by Eqs. (12)-(13) (Table 3).

After the information entropy of the \( i \)th index is determined, the entropy weight \( u_i \) of the \( i \)th index can be obtained by Eq. (14).
The index weights of the six BWI-related factors were calculated by Eq. (14) (Table 4).

### 3.1.3. BWI risk calculation

The formula to calculate the BWI risk at any coordinate position in the area is as follows:

\[ V = \sum_{i=1}^{m} u_i r_i, \]  

where \( V \) refers to the BWI risk index; \( r_i \) refers to the standardized value of the \( i^{th} \) related factor at the coordinate point to be evaluated; \( u_i \) refers to the weight of the \( i^{th} \) related factor; and \( m \) refers to the number of evaluation indicators.

The values of various related factors exposed by each drill hole in the study area were obtained by measurements/calculation (Tables 5–7). Then, Eq. (15) was used to obtain the value of \( V \) at each drill hole. Finally, the value of \( V \) at each coordinate point in the mining area was obtained using interpolation. The distribution of \( V \) values in mining areas 201 and 106 A in the Shilawusu mine is shown in Figure 15. Respective values were in the ranges of 0.26-0.39 and 0.38-0.42. Overall, the BWI risk in mining area 106 A was greater than that in area 201.

To ensure that the obtained boundary values were applicable in the Shilawusu, Yingpanhao, and Cuimu mines, the data were processed using the same standards. For example, when standardizing mining thickness data from the Shilawusu mine with Eqs. (10)-(11), the maximum/minimum values for mining thicknesses were the same across all three coal mines. The reference values used for data standardization of BWI-related factors in the three coal mines are shown in Table 8.

### 3.2. Overall BWI risk index in the bed-separation zone at different excavation lengths

Because the BWI is induced by rock layer fracturing, which occurs across a certain span length, it is meaningless to obtain the BWI risk at a given coordinate point. Instead, the overall risk in a specific bed-separation zone should be estimated. To calculate this risk at different excavation lengths, the following theories and methods were adopted.

1) According to stress balance arch theory, when the balance arch is extended to the limit arch, the span and height of the arch does not increase with excavation.

### Table 4. Index weight of BWI-related factors.

| M  | \( T_c \) | \( \Phi \) | \( T_l \) | \( P_m \) | \( P_s \) |
|----|----------|----------|----------|----------|----------|
| \( u_1 = 0.06 \) | \( u_2 = 0.30 \) | \( u_3 = 0.21 \) | \( u_4 = 0.13 \) | \( u_5 = 0.15 \) | \( u_6 = 0.15 \) |
length but exists in the form of a moving arch. As shown in Figure 17, each excavation length corresponds to a specific bed-separation zone with a defined distribution range.

Table 5. BWI-related factors exposed by drill holes in the Shilawusu mine.

| Drill hole | X    | Y    | M (m) | Tc (m) | Φ (%) | Tj (m) | Pe | Ps |
|------------|------|------|-------|--------|-------|--------|----|----|
| K14        | 381974.14 | 4322535.04 | 4.98 | 21.49 | 50.53 | 161.53 | 15.65 | 20.12 |
| K22        | 381973.48 | 4322007.56 | 4.58 | 31.81 | 42.32 | 202.76 | 16.38 | 11.12 |
| K29        | 381973.64 | 4321507.56 | 5.15 | 22.23 | 81.04 | 214.42 | 18.01 | 13.15 |
| K13        | 381480.2 | 4322538.13 | 4.65 | 18.36 | 63.21 | 204.92 | 14.68 | 23.09 |
| K08        | 381968.16 | 4320303.45 | 4.54 | 20.08 | 45.97 | 185.1 | 11.66 | 19.74 |
| K15        | 382473.13 | 4322527.74 | 4.85 | 24.25 | 56.64 | 210.75 | 19.23 | 18.02 |
| K21        | 381490.38 | 4322017.86 | 5.4 | 18.83 | 72.11 | 214.65 | 18.01 | 13.15 |
| K23        | 382485.52 | 4322012.65 | 4.42 | 25.44 | 38.2 | 211.89 | 7.75 | 3.15 |
| K28        | 381479.08 | 4321533.89 | 5.5 | 24.41 | 12.39 | 188.36 | 21.19 | 16.03 |
| K12        | 380962.39 | 4322535.57 | 5.5 | 19 | 25.21 | 123.86 | 18.21 | 6.6 |
| K27        | 380973.92 | 4321536.21 | 5.5 | 21.69 | 20.9 | 208.7 | 6.17 | 21.48 |
| K30        | 382414.75 | 4321522.83 | 4.85 | 21.09 | 28.49 | 191.51 | 19.67 | 11.82 |

Table 6. BWI-related factors exposed by drill holes in the Yingpanhao mine.

| Drill hole | X    | Y    | M (m) | Tc (m) | Φ (%) | Tj (m) | Pe | Ps |
|------------|------|------|-------|--------|-------|--------|----|----|
| K9-8       | 36586833.18 | 4259050.82 | 5.6 | 20.62 | 3.42 | 177.84 | 19.05 | 19.01 |
| K9-7       | 36586337.54 | 4259058.24 | 5.6 | 22.17 | 0 | 165.28 | 17.14 | 21.47 |
| K9-6       | 36585815.95 | 4259048.93 | 5.6 | 20.41 | 4.04 | 165.46 | 14.7 | 13.56 |
| K9-5       | 36585344.35 | 4259045.28 | 5.6 | 22.53 | 10.45 | 148.01 | 16.57 | 10.78 |
| K9-4       | 36584882.47 | 4259021.84 | 5.6 | 27.54 | 26.8 | 170.92 | 13.07 | 16.39 |
| K9-3       | 36584336.82 | 4258980.89 | 5.6 | 28.37 | 10.48 | 172.1 | 19.33 | 19.11 |
| K9-2       | 36583827.38 | 4258913.59 | 5.6 | 25.92 | 21.66 | 177.04 | 17.92 | 20.03 |
| K9-1       | 36583356.47 | 4258921.39 | 9.03 | 18.1 | 34.41 | 123.75 | 21.54 | 16.28 |
| K7-1       | 36583331.24 | 4259969.55 | 5.6 | 29.75 | 80.58 | 165.56 | 22.31 | 19.11 |
| K7-2       | 36583796.4 | 4259932.16 | 5.6 | 34.2 | 38.84 | 158.99 | 12.75 | 23.55 |
| K7-3       | 36583439.2 | 4260017.86 | 5.6 | 31.51 | 40.34 | 156.8 | 15.68 | 22.97 |
| K7-4       | 36583873.45 | 4260005.63 | 5.6 | 31.67 | 5.54 | 173.2 | 7.4 | 18.45 |
| K7-5       | 36583545.56 | 4260020.62 | 5.6 | 37 | 42.76 | 158.15 | 14.86 | 22.85 |
| K7-6       | 36585810.8 | 4260017.87 | 5.6 | 23.07 | 47.31 | 161.32 | 15.86 | 16.93 |
| K7-7       | 36586316.32 | 4260054.68 | 5.6 | 36.83 | 11.01 | 164.13 | 15.64 | 18.19 |
| K7-8       | 36586823.19 | 4260075.1 | 5.6 | 26.72 | 52.08 | 194.15 | 21.99 | 16.98 |
2) When the overall BWI risk in a given bed-separation zone corresponding to a certain excavation length is obtained, the BWI threat at this excavation length can be obtained.

3) In a bed-separation zone corresponding to a given excavation length, the overall risk is obtained by calculating the average risk for all grid points. In this study, each bed-separation zone was divided into squares with lengths of 10 m to facilitate calculation.

As shown in Figure 17, the “out-of-arch zone” refers to the bed-separation zone extension area outside of the stress balance arch. Because the strata in the area outside the arch are not in the stress release area, there were no large-scale bed separations in the out-of-arch zone. Therefore, the out-of-arch zone was considered a safe zone. The length of the initial overhanging zone refers to the span of the bottom rock layer in the Cretaceous strata before the first fracture. The first fracture in the Cretaceous strata occurred when the span of the Cretaceous bed-separation zone in the stress balance arch exceeded the length of the initial overhanging zone, and a BWI from the Cretaceous strata may have occurred. Therefore, the initial overhanging zone was considered to be a safe zone. Mining practice has proven that the height

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**Table 7.** BWI-related factors exposed by drill holes in the Cuimu mine.

| Drill hole | X (m)     | Y (m)     | M (m) | T (m) | Φ (%) | T (m) | Pm | Ps |
|------------|-----------|-----------|-------|-------|-------|-------|----|----|
| K6-1       | 36484886.24 | 3861009.84 | 12    | 27.55 | 100   | 0     | 13.71 | 5.5 |
| K6-2       | 36484840.1 | 3860590.134 | 12    | 19.73 | 98.87 | 0     | 6.42 | 9.69 |
| K6-3       | 36484858.59 | 3860132.065 | 12    | 25.11 | 100   | 0     | 14.25 | 4.52 |
| X7-2       | 36485309.63 | 3860369.594 | 12    | 34    | 100   | 0     | 13.67 | 7.23 |
| X7-3       | 36485177.31 | 3859602.365 | 9.5   | 29.33 | 100   | 0     | 3.15  | 2.58 |

**Table 8.** Reference values for data standardization.

| Data type | M (m) | T (m) | Φ (%) | T (m) | Pm | Ps |
|-----------|-------|-------|-------|-------|----|----|
| Maximum values | 12    | 45.56 | 100   | 214.65 | 25.47 | 25.35 |
| Minimum values | 4.42  | 17.75 | 0     | 0     | 2.76 | 0  |

**Figure 17.** Definition of terms in the overall BWI risk assessment: Q-Quaternary; K-Cretaceous; J-Jurassic; ①, ④-Out-of-arch zone; ②-Initial overhanging zone; ③-Shared zone covered by safe zone and transition zone; ④-Shared zone covered by transition zone and danger zone; a-Excavation length when the stress arch extends to the bed-separation zone in the Cretaceous strata; b-Excavation length when the bottom rock layer in the Cretaceous strata breaks for the first time; c-Excavation length when stress arch expands to the limit arch.
of the limit arch is 0.5-0.7 times the mining depth. In this study, 0.7 times the mining depth was used as the limit arch height. The length of the out-of-arch zone and the initial overhanging zone in each mining area are shown in Table 9.

### 4. Results and discussion

The lengths of mining areas 201 and 106 A in the Shilawusu mine were 825.8 m and 1143.86 m, respectively. The overall BWI risk index in the bed-separation zone corresponding to different excavation lengths in the Shilawusu mine is shown in Figure 18.

Figure 18 shows that the risk index distribution ranges for mining areas 201 and 106 A were 0.296-0.371 and 0.421-0.445, respectively. Since there was no large-scale BWI in mining area 201, the area with a risk index less than or equal to 0.371 was classified as the safe zone. Due to the large-scale water inrush in mining area 106 A, the area with a risk index greater than or equal to 0.421 was classified as a danger zone. The area with a risk index between 0.371 and 0.421 was regarded as a transition zone (Figure 19).
As shown in Figures 17 and 19, when the excavation length was less than or equal to $a$, the stress arch was too small to expand into the Cretaceous strata, which resulted in no BWI in the Cretaceous strata. When the excavation length was between $a$ and $b$, although the stress arch expanded into the Cretaceous strata, the length of the Cretaceous bed-separation zone in the stress arch was too small to cause the fracture of the bottom Cretaceous strata and the occurrence of a BWI. When the excavation length was greater than $b$, the balance arch expanded with increasing excavation length, breaking more strata in the stress arch and potentially causing a BWI.

When the overall BWI risk index in the bed-separation zone that corresponded to a certain excavation length was in the safe zone, it indicated that there would not be a large BWI at that excavation length. In contrast, when the overall risk index that corresponded to a certain excavation length was in the danger zone, the potential for a large BWI at that length was high. The excavation length corresponding to the danger zone is called the danger excavation length. Because rock fractures, bed-separation water accumulation, and the recovery of fracture zone water resistance require time, the occurrence of BWIs is accidental. In other words, a BWI does not occur at every dangerous excavation length but only at individual dangerous excavation lengths. Although it is difficult to predict the excavation length for BWIs, the range in length can be predicted, and the range of values is the distribution range of the danger excavation length.

The method proposed in this paper determined the overall BWI risk index in the bed-separation zone that corresponded to different excavation lengths. It has the following advantages.

1) The proposed method considers the fact that BWI occurrence is determined by overall risk in a specific bed-separation zone, so the evaluation results more closely correspond to actual situations.
2) When evaluating the BWI risk for a given excavation length, it is more practical to only consider the bed-separation water inrush in the stress arch corresponding to the excavation length. The method proposed in this paper allows us to obtain the actual threat of BWIs at different excavation lengths, which is beneficial to the prevention and control of water hazards.

3) The determination of the boundary values between different risk levels is more reasonable than the natural classification method in ArcGIS, and the obtained boundary values are universal across the three mines.

Figure 20. Comparison of water inflow in mining areas 108 and 106A in the Shilawusu mine.

Figure 21. Overall BWI risk index in the bed-separation zone corresponding to different excavation lengths in each of the tested areas in the Shilawusu mine.
Figure 22. BWI risk zoning in each mined area in the Shilawusu mine.

Figure 23. Overall BWI risk index in the bed-separation zone corresponding to different excavation lengths in each tested area in the Yingpanhao mine.
5. Application and validation

5.1. Shilawusu coal mine

Mining in area 201 A was completed in 2018, and BWIs did not occur during mining. Mining in area 108 is still in progress, and until August 2020, approximately 1000 m had been excavated. A BWI similar to that in mining area 106 A did not occur in the excavation process of the first 1000 m of area 108 (Figure 20).

Figures 21 and 22 show that mining area 201 A was in the safe zone during the mining period, which was consistent with the observed situation; mining area 108 was also in the safe zone for the first 1000 m, which was also consistent with the observed situation.

Figure 24. BWI risk zoning in each Yingpanhao mining area.

Figure 25. Water inflow variability during mining in area 21301 in the Cuimu mine.

5. Application and validation

5.1. Shilawusu coal mine

Mining in area 201 A was completed in 2018, and BWIs did not occur during mining. Mining in area 108 is still in progress, and until August 2020, approximately 1000 m had been excavated. A BWI similar to that in mining area 106 A did not occur in the excavation process of the first 1000 m of area 108 (Figure 20).

Figures 21 and 22 show that mining area 201 A was in the safe zone during the mining period, which was consistent with the observed situation; mining area 108 was also in the safe zone for the first 1000 m, which was also consistent with the observed situation.
5.2. Yingpanhao coal mine

Mining in areas 2101, 2102 and 2201 was completed in 2019, and BWIs did not occur during mining. Mining in area 2202 was still in progress, and until August 2020, approximately 1000 m had been excavated. No BWI occurred during the excavation process of the first 1000 m in area 2202.

Figures 23 and 24 show that mining areas 2101 and 2102 were in the safe zone during the whole mining period and that BWIs did not occur, which was consistent...
with observations. There was no danger zone in areas 2202 and 2201, which had only transitions and were dominated by safe zones. No BWI occurred in those mining areas, which was consistent with observations.

5.3. Cuimu coal mine

Mining in areas 21301 and 21302 was completed in 2013 and 2014, respectively. Large BWIs occurred many times in these two areas during mining. For example, in area 21301, when the excavation length was 345 m, 495 m, 785 m and 841 m, large-scale BWIs occurred (Figure 25).

In areas 21301 and 21302, all areas except for the out-of-arch zone and initial overhanging zone were in the danger zone, which had a risk index much greater than the boundary value between the transition and danger levels (Figures 26 and 27). Therefore, large-scale BWIs occurred in these two mining areas, which was consistent with observations.

6. Conclusions

The Ordos Basin has geological preconditions for the formation of BWIs in Cretaceous strata. Bed-separation water exists in the Cretaceous strata and at the interface between the Cretaceous and Jurassic strata, which is a threat to mining. Therefore, the assessment of Cretaceous bed-separation water hazards is indispensable and meaningful for hazard assessment. In traditional BWI evaluation methods, the threat of BWIs corresponding to any excavation length is not evaluated, there is no basis for the determination of boundary values between different risk levels, and the obtained boundary values are not universal. The contribution of this paper is to establish a method for evaluating the overall risk of Cretaceous BWIs at different excavation lengths in the Ordos Basin and to determine boundary values that separate different levels of risk.

BWI risk assessment was realized by using multifactor superposition, and six BWI-related factors were investigated in detail: $M$, $T_C$, $\Phi$, $T_p$, $P_m$ and $P_s$. $P_m$ was used as an index to evaluate the self-healing effect of mudstone fractures and was positively correlated with mudstone layer thickness and negatively correlated with the available settlement space. $P_s$ was used as an index to evaluate the filling effect of sandstone fractures and was positively correlated with sandstone layer thickness and negatively correlated with the available settlement space. Mining areas 106 A and 201 in the Shilawusu mine were selected as an example. The weights for the six BWI-related factors were obtained using the entropy weight method, and then the BWI risk index at any coordinate point was calculated by multifactor superposition. Then, the overall BWI risk index in a given bed-separation zone corresponding to any excavation length was calculated using stress balance arch theory.

The boundary values between different risk levels were obtained by comparing the overall risk in mining areas with and without BWIs. Because the three coal mines in the Ordos Basin selected in this paper were evaluated together, all data were processed according to a unified standard, which ensured that the determined boundary
values were applicable across all three mines. Using the method established in this paper, BWI risk in other mined areas of the Ordos Basin was evaluated and validated. Accurate evaluation results are of great significance for the control of water hazards during mining, with significant implications for miner safety and hazard management.

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Disclosure statement

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

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