Research Article

Research on the Reasonable Width of the Waterproof Coal Pillar during the Mining of a Shallow Coal Seam Located Close to a Reservoir

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Received 4 June 2019; Revised 23 September 2019; Accepted 11 November 2019; Published 16 December 2019

Academic Editor: Paolo Castaldo

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Retaining a waterproof coal pillar is the most effective water conservation method for coal seam mining close to a reservoir, and determining a reasonable width for the waterproof coal pillar has been a common problem among mining scholars for a considerably long time. In case of mining a 4−2 coal seam close to the Changjiagou Reservoir in the Zhangjiamao mine, the research methods of theoretical analysis, physical simulation using similar materials, and numerical simulation have been adopted to analyze the overburden strata mining failure features and the surface subsidence law. Additionally, the influences of the width of the coal pillar on the reservoir bank slope stability have been investigated. The results denote that a coal pillar can be divided into a mine-pressure-influenced zone, an effective waterproof zone, and a water-level-influenced zone with respect to water resistance. Furthermore, the width of the waterproof coal pillar was determined to be 107.41 m by theoretical analysis. The simulation test indicated that when the working face advanced close to the reservoir, the reservoir bank exhibited vertical downward as well as transverse abscission layer fractures and the divided topsoil slipped toward the reservoir. Subsequently, the judgment conditions required for determining the critical width of the waterproof coal pillar were proposed based on the requirements to prevent the reservoir bank slope from instability failure and the water gushing accident in goaf. The maximum width of the waterproof coal pillar when the top point on the slope surface experienced reverse horizontal displacement and several key points produced sharp vertical displacements or when the pore pressure in the coal seam roof and floor suddenly became 0 was considered to be the critical width. Furthermore, the critical width was determined to be 96 m via simulation analysis, verifying the rationality of the theoretical method. These results could provide a theoretical basis for determining the width of the waterproof coal pillar of the coal seam located close to a reservoir.

1. Introduction

China’s western regions of Inner Mongolia, Ningxia, Gansu, and northern Shaanxi exhibit a fragile ecological environment [1] and abundant high-quality coal resources with a high degree of resource enrichment. This is particularly true in case of the Jurassic coal field in northern Shaanxi, exhibiting a simple structure and a dip angle of generally 1°–3°. The coal seam in this field is stable and mostly contains long-flame and noncaking coals that contain extremely low amounts of sulfur, phosphorus, and ash and exhibit mid-to-high calorific values. This is a rare high-quality type of coal used by the power, liquefaction, and chemical industries at home and abroad. The Jurassic coal field in northern Shaanxi is the largest coalfield in proven reserves in China [2], increasing its application prospects with respect to mining. However, the ecological environment is very fragile, and the water resources are scarce in the northern Shaanxi coalfield bordering the desert and loess plateau. More than 30 years of mining has led to an inrush of water and sand into the mine,
a decline in the groundwater level, and massive losses of surface water and groundwater sources that can cause environmental problems such as the drying of lakes, river flow attenuation, and environmental deterioration in river areas [3–5]. The water scarcity issues and relevant eco-environmental issues have become important factors that restrict the production, construction, and sustainable development with respect to the Jurassic coalfield in northern Shaanxi, and water conservation mining has been one of the main methods to address the issues caused by mining in this region [6–9]. In case of coal seam mining, the stresses of the surrounding rocks are redistributed, causing loosening deformation and failure fractures [10–12]. When the water-conducting fractures connect with a water body, such as an aquifer or confined water near the coal seam, the water would flow into the roadway, resulting in water inrush accidents at mines [13–15]. Currently, retaining a waterproof coal pillar is considered to be the most effective method for water conservation mining. Scholars have researched the determination of the width of the waterproof coal pillar in the cases of coal seam mining under an aquifer and adjacent to water-conducting fault and that of the section coal pillar, which are listed in Table 1. In these research studies, the failure characteristics of the surrounding rocks that can be attributed to coal seam mining were considered; furthermore, the plastic failure zone and elastic waterproof zone were established on the side of a coal pillar near the roadway, and the failure range caused by high water pressure in deep-buried strata or fault was considered on the side of the influence sources. However, the movement of the overlying strata, the development of fractures, and the influence of water body on stopes vary widely during the mining process of the working faces because of the complexity of the geological structures of strata and the differences in mining conditions. For the shallow coal seams located close to a reservoir, no effects of high water pressure can be observed; however, the distribution of the phreatic line in the bank slope is intended to prevent the reservoir water from conducting the surrounding rock fracture area. In addition, the slope stability should be considered during mining to ensure the safe operation of the reservoir. Currently, there has been no research on this aspect. Herein, we used a 4−2 coal seam in the Zhangjiamao mine near the Changjiagou Reservoir as the study project and studied the failure characteristics of the overlying strata and reservoir bank slope during the mining process using theoretical analysis, physical simulations using similar materials, and numerical simulation. Furthermore, we analyzed the variations in stress, displacement, and pore water pressure during mining and established a reasonable waterproof coal pillar width. Our results could provide a theoretical basis for determining the widths of the waterproof coal pillar in case of coal seam mining close to reservoirs.

2. Engineering Background

Large-scale coal seam mining was initiated in the ecologically vulnerable areas of northern Shaanxi in 1987. By the end of 2008, Yulin City’s coal-bearing area accounted for 54% of its total land area, with predicted and proven coal reserves of 271.4 and 146 billion tons, respectively. These reserves are obtained from the Shen-fu, Yu-shen, and Yu-heng mining areas. Yulin City is considered to be an important modern coal production base in China. Honggijiao Lake, which is the largest freshwater lake in an inland desert, Changjiagou Reservoir, Yaozheng Reservoir, and Tuweihe Reservoir are located in the Shen-fu and Yu-shen mining areas. The water-holding area of the Changjiagou Reservoir is approximately 0.3 km², its catchment area is approximately 44 km², and all the main distribution rivers stem from the Yellow River. The Zhangjiamao coal mine is located near the Changjiagou Reservoir. The first mining coal seam is a 4−2 coal seam with a burial depth of 67 m and a thickness of 3.5 m. The location of the 4−2 coal seam relative to the Changjiagou Reservoir is denoted in Figure 1. The flood level of the reservoir is 27 m, 14 m higher than the roof of the 4−2 coal seam. Figure 2 shows the distribution of the 4−2 coal seam overlying strata. Ten rock and soil strata are present at the depth being researched. The physical and mechanical parameters of each stratum are presented in Table 2.

3. Theoretical Analysis of the Width of the Waterproof Coal Pillar

In case of a coal seam located close to a reservoir (Figure 3), part of the coal seam is located below the saturation line of the reservoir bank slope if the reservoir’s water level is higher than the floor of the coal seam. However, the stresses of the surrounding rock are redistributed and the coal seam around the roadway is destroyed when the coal seam roadway is being excavated; subsequently, cracks gradually begin to deepen. Thus, the water in the reservoir will flow into the roadway through the coal seam if the destroyed section of the coal seam around the roadway is connected to the section beneath the saturation line of the reservoir bank slope. For effective waterproofing of the coal pillar, a section must be maintained intact between them. Therefore, a waterproof coal pillar can be divided into a mine-pressure-influenced zone \( L_1 \), an effective waterproof zone \( L_2 \), and a water-level-influenced zone \( L_3 \). Thus, the width of a waterproof coal pillar can be expressed as follows:

\[
L = L_1 + L_2 + L_3, \tag{1}
\]

where \( L \) denotes the width of the waterproof coal pillar, \( L_1 \) denotes the width of the mine-pressure-influenced zone, \( L_2 \) denotes the width of the effective waterproof zone, and \( L_3 \) denotes the width of the water-level-influenced zone, which is influenced by the saturation line of the reservoir bank and represents the width of the coal seam within the saturation line.

3.1. Mine-Pressure-Influenced Zone and Effective Waterproof Zone. Based on this analysis, the mine-pressure-influenced zone is related to the plastic failure zone in the coal seam around the roadway. The coal mass in the mine-pressure-
Table 1: Determination methods of the widths of waterproof coal pillars in different conditions.

<table>
<thead>
<tr>
<th>Coal seam mining in different cases</th>
<th>Width of waterproof coal pillar</th>
<th>Considered influence factors</th>
</tr>
</thead>
</table>
| **Under an aquifer**               | The height of water-conducting fracture zone + the thickness of the protective layer | (1) Lithology of overlying strata [16, 17]  
(2) Dip angle of coal seam [18, 19]  
(3) Key stratum [20–23]  
(4) Changes of the characteristic parameters of overlying strata [24, 25]  
(5) Height of coal seam [20, 26]  
(6) Depth of coal seam [3, 27]  
(7) Stability of coal pillar [20, 28]  
(8) Water pressure and mine pressure [17] |
| **Adjacent to the water-conducting fault** | (1) The empirical formula considered the effects of water pressure  
(2) A coal-mining-influenced zone + an elastic waterproof zone + a fault-affected zone | (1) Water pressure and mine pressure [29–33]  
(2) Dip angle of fault [29–31] |
| **In section**                     | A plastic zone + an elastic core zone + a hydraulic fractured zone | (1) Stability of coal pillar [34, 35]  
(2) Water pressure and mine pressure [36] |
| **Close to a reservoir**           | A mine-pressure-influenced zone + an effective waterproof zone + a water-level-influenced zone | (1) Water level and the distribution of the phreatic line in the bank slope (in this paper)  
(2) Stability of the bank slope (in this paper) |

![Figure 1: Location of the 4-2 coal seam relative to the reservoir.](image)

![Figure 2: Typical geological log profile of 4-2 coal seam overlying strata.](image)
The effective waterproof zone plays a major role in preventing the water in the coal seam located below the saturation line from flowing into the goaf. The width of this zone can be calculated by the formula for obtaining the width of the waterproof coal pillar in case of water-bearing or water-conducting faults that can be given as [29]

\[ L_2 = 0.5\alpha_1 h_1 \sqrt{\frac{3P_0}{\sigma_t}} \]  

where \( \alpha_1 \) is a safety coefficient that is typically 2–5, \( h_1 \) is the coal seam thickness, \( P_0 \) is the head pressure, and \( \sigma_t \) is the coal seam tensile strength. \( L_2 \) should not be less than 20 m.

3.2 Water-Level-Influenced Zone. The water-level-influenced zone is related to the width of the coal pillar within the saturation line of the reservoir bank slope when the reservoir exhibits the highest water level. Therefore, the major issue is to determine the saturation line of the reservoir bank slope. To simplify this problem, it is assumed that the reservoir
bottom is an impervious surface and that the reservoir bank slope comprises homogeneous rock and soil.

Dachler introduced a piecewise method, where a dam was divided into an upper wedge section, a middle seepage section, and a lower wedge section, to analyze the seepage of homogeneous soil dams with an impervious foundation [38]. Furthermore, the reservoir bank slope can be divided into an upper wedge section and a main seepage section considering the similarities between the reservoir bank seepage and that of a soil dam. The simplified model is presented in Figure 4.

In Figure 4, $m_1$ is the reservoir bank slope ratio, $h$ is the reservoir’s water level, $x_0$ is the abscissa of the saturation line on the border between the upper wedge and main seepage section, $h_0$ is the height of the saturation line on the border between the upper wedge and main seepage sections, $x_1$ is the width of the main seepage section in the $x$ direction, $H$ is the coal seam burial depth, $h_1$ is the coal seam thickness, $h_2$ is the height of the floor of the coal seam relative to the reservoir bottom, $h_3$ is the hydraulic head of the boundary of the main seepage section in the affected area, $L_0$ is the length of the boundary region in which the head is not affected by the variation in the water level of the reservoir, and $L_3$ is the width of the coal pillar in the water-level-influenced zone.

In the upper wedge section (section AB: $0 \leq x \leq x_0$), the saturation line is a straight line that passes through the point $(0, h)$ with a slope of $-m_1$. Thus, the saturation line in this section can be expressed as

$$y = h - m_1 x. \quad (4)$$

Based on the empirical formula proposed by Dachler, the flow $q$ can be expressed as

$$q = K (h - h_0) \left(1.12 + \frac{1.93}{m_1}\right). \quad (5)$$

In the main seepage section (section BC: $x_0 \leq x \leq x_0 + x_1$), Dupuit’s formulas are satisfied, i.e.,

$$y = \left[h_3^2 + (h_0^2 - h_3^2) \frac{x_0 + x_1 - x}{x_1}\right]^{0.5}, \quad (6a)$$

$$q = K \frac{h_0^2 - h_3^2}{2x_1}. \quad (6b)$$

Because the flow between the saturation line and impervious line is equal in each cross section,

$$K (h - h_0) \left(1.12 + \frac{1.93}{m_1}\right) = K \frac{h_0^2 - h_3^2}{2x_1}. \quad (7)$$

From Figure 4, it can be observed that

$$x_1 = L_0 - x_0 - x_2. \quad (8)$$

In addition,

$$x_0 = \frac{1}{m_1} (h - h_0). \quad (9)$$

By substituting equations (8) and (9) into equation (7), $h_0$ can be obtained as

$$ah_0^2 + bh_0 + c = 0, \quad (10)$$

where

$$a = 1 + \frac{2}{m_1} \left(1.12 + \frac{1.93}{m_1}\right), \quad (10a)$$

$$b = 2 \left(1.12 + \frac{1.93}{m_1}\right) \left[L_0 - x_2 - \frac{2h}{m_1}\right], \quad (10b)$$

$$c = 2 \left(1.12 + \frac{1.93}{m_1}\right) \frac{1}{m_1} h^2 - (L_0 - x_1) h - h_3^2. \quad (10c)$$

By solving equation (10), $h_0$ can be obtained as

$$h_0 = \frac{-b + \sqrt{b^2 - 4ac}}{2a}. \quad (11)$$

$x_0$ and $x_1$ are calculated using equations (8) and (9), and the abscissa of the intersection of the coal seam with a height of $h_2$ and the saturation line can be expressed as

$$x = x_0 + x_1 - \frac{h_2^2 - h_3^2}{h_0^2 - h_3^2} x_1. \quad (12)$$

By adding the coal pillar width to the slope on the right side of the $y$-axis, the water-level-influenced zone can be expressed as

$$L_3 = m_1 (h - h_2) + x_0 + x_1 - \frac{h_2^2 - h_3^2}{h_0^2 - h_3^2} x_1. \quad (13)$$

It should be noted that the calculations assume homogeneous rock and soil strata. Table 2 shows that apart from the 2.2 m immediate roof above the 4 m coal seam, the actual stratum comprises fine-grained sandstone that is more than 20 m thick above and below the coal seam, which is located reasonably close to the homogeneous stratum assumed for the aforementioned seepage analysis. Therefore, calculation of the water-level-influenced zone $L_3$ using equation (13) exhibits some reliability.

Furthermore, the width of the waterproof coal pillar in a coal seam close to a reservoir could be calculated by substituting equations (2), (3), and (13) into equation (1).

### 3.3 Calculation of the Width of the Waterproof Coal Pillar

The width of the mine-pressure-influenced zone can be calculated using equation (2) based on the waterproof coal pillar (Section 3.1). Here, $m$ is the coal seam mining thickness, $\gamma$ is the average rock strata volume weight, and $H$ is the roadway depth (Table 2). Furthermore, $A$ is the lateral pressure coefficient of the coal mass obtained as $(1 = -\sin \varphi)$. Here, $\varphi$ is the friction coefficient of coal mass (Table 2). $c_0$ and $\varphi_0$ are the cohesive force and friction coefficients between the coal seam and rock strata in the roof and floor, respectively. $P$ is the support resistance of the coal seam (0–300 kPa), and $k$ is the stress concentration factor. $c_0$, $\varphi_0$, $P$, and $k$ are determined to be in the reasonable range recommended in reference [22]. Then, by inputting $m = 3.5$ m, $\gamma = 24.7$ kN/m$^3$, $H = 67$ m, $c_0 = 392$ kPa, $\varphi_0 = 20^\circ$, $a = 1 + \frac{2}{m_1} \left(1.12 + \frac{1.93}{m_1}\right)$, $b = 2 \left(1.12 + \frac{1.93}{m_1}\right) \left[L_0 - x_2 - \frac{2h}{m_1}\right]$, $c = 2 \left(1.12 + \frac{1.93}{m_1}\right) \frac{1}{m_1} h^2 - (L_0 - x_1) h - h_3^2$. $h_0$ can be obtained as

$$ah_0^2 + bh_0 + c = 0, \quad (10)$$

where

$$a = 1 + \frac{2}{m_1} \left(1.12 + \frac{1.93}{m_1}\right), \quad (10a)$$

$$b = 2 \left(1.12 + \frac{1.93}{m_1}\right) \left[L_0 - x_2 - \frac{2h}{m_1}\right], \quad (10b)$$

$$c = 2 \left(1.12 + \frac{1.93}{m_1}\right) \frac{1}{m_1} h^2 - (L_0 - x_1) h - h_3^2. \quad (10c)$$

By solving equation (10), $h_0$ can be obtained as

$$h_0 = \frac{-b + \sqrt{b^2 - 4ac}}{2a}. \quad (11)$$

$x_0$ and $x_1$ are calculated using equations (8) and (9), and the abscissa of the intersection of the coal seam with a height of $h_2$ and the saturation line can be expressed as

$$x = x_0 + x_1 - \frac{h_2^2 - h_3^2}{h_0^2 - h_3^2} x_1. \quad (12)$$

By adding the coal pillar width to the slope on the right side of the $y$-axis, the water-level-influenced zone can be expressed as

$$L_3 = m_1 (h - h_2) + x_0 + x_1 - \frac{h_2^2 - h_3^2}{h_0^2 - h_3^2} x_1. \quad (13)$$

It should be noted that the calculations assume homogeneous rock and soil strata. Table 2 shows that apart from the 2.2 m immediate roof above the 4 m coal seam, the actual stratum comprises fine-grained sandstone that is more than 20 m thick above and below the coal seam, which is located reasonably close to the homogeneous stratum assumed for the aforementioned seepage analysis. Therefore, calculation of the water-level-influenced zone $L_3$ using equation (13) exhibits some reliability.

Furthermore, the width of the waterproof coal pillar in a coal seam close to a reservoir could be calculated by substituting equations (2), (3), and (13) into equation (1).
\[ \varphi = 33.64\textdegree, A = 0.45, P = 20\text{kPa}, \text{and} \ k = 2 \text{ into equation (2),} \]

we obtain \( L_1 = 6.67\text{ m}. \)

Furthermore, the width of the effective waterproof zone can be calculated using equation (3). Here, \( h_1 \) is the coal seam thickness, and \( \sigma \) is the coal seam tensile strength (Table 2). \( \alpha_1 \) is a safety coefficient that is typically 2–5, and \( \rho_0 \) is the head pressure calculated based on the considered water level. Then, by considering \( \alpha_1 = 4, h_1 = 3.5, \rho_0 = 175\text{kPa}, \) and \( \sigma = 1370\text{kPa}, \) we obtain \( L_2 = 4.33\text{ m}. \) Because \( L_2 \) should not be less than \( 20\text{ m}, L_3 \) is considered to be \( 20\text{ m}. \)

The width of the water-level-influenced zone can be calculated using equation (13). Here, \( m_1 \) is the reservoir bank slope ratio, \( h \) is the reservoir’s water level, \( H \) is the coal seam burial depth, \( h_1 \) is the coal seam thickness, \( h_2 \) is the floor height of the coal seam relative to the reservoir bottom, \( h_3 \) is the hydraulic head of the main seepage section boundary in the affected area, and \( L_0 \) is the length of the boundary region in which the head is unaffected by the variation in the water level of the reservoir. \( m_1, h, H, \) and \( h_2 \) are the known model parameters. \( L_0 \) and \( h_3 \) are the boundary condition parameters, which can be obtained by monitoring the variation in the stratum water level. Then, by considering \( m_1 = 1.19, h = 27, h_1 = 0, L_0 = 80, x_2 = 32.18, \) and \( h_2 = 9.5, x_0 = 5.24, h_0 = 20.75, \) and \( L_3 = 92.92\text{ m} \) can be obtained.

By substituting the results of \( L_1, L_2, \) and \( L_3 \) into equation (3), we can obtain \( L = L_1 + L_2 + L_3 = 6.67 + 20 + 62.92 = 89.59\text{ m}. \)

These analyses do not consider the influences of the physical and mechanical properties of the overlying strata, mining methods, support technologies, or mechanical properties of the coal seam floor and roof. Therefore, we have introduced a safety factor \( \beta \) to revise equation (1):

\[ L = \beta(L_1 + L_2 + L_3). \]  

By considering \( \beta = 1.2, \) the reasonable width of the waterproof coal pillar can be determined to be \( 107.51\text{ m}. \)

**4. Model Test of the Overlying Strata and Slope Stability in Coal Seam Mining**

**4.1. Test Scheme of the Physical Model with Similar Materials.** We developed a physical model using similar materials to study the failure modes of the overlying strata and reservoir bank slope caused by coal seam mining based on the geological conditions of the overlying strata of the \( 4^{-2} \text{ coal seam} \) located close to the Changjiagou Reservoir. Using the current test conditions and geological conditions of the \( 4^{-2} \text{ coal seam} \) overlying strata, the size of the test model was determined to be \( 5.0\text{ m} \times 0.2\text{ m} \times 1\text{ m} \) (length) \times (width) \times (height). Additionally, the model’s geometric similarity proportion is \( 1:100, \) gravity acceleration similarity proportion is \( 1:1, \) and bulk density similarity proportion is \( 2:3. \)

Based on the similarity principle of the physical model, the time similarity proportion, displacement similarity proportion, and stress similarity proportion were \( 1:10, 1:100, \) and \( 1:150, \) respectively. Therefore, \( 1\text{ cm} \) in the model represents \( 1\text{ m} \) in the prototype.

River sand, gypsum, lime powder, and fly ash were selected as the main materials of the physical model. Based on the requirements of the bulk density similarity proportion and stress similarity proportion, the orthogonal test was adopted to determine the proportion schemes for similar simulated rock strata materials as shown in Table 3, and the errors of the uniaxial compressive strengths of similar materials with theoretical values are controlled to be within \( 5\%. \) When lying, mica powder is evenly scattered to simulate the stratified weak plane.

To analyze the influence of the water level of the reservoir on slope stability, we designed an equal-water-level storage bottle to simulate the seepage of water into the slope through water-conducting fractures during mining. Five water storage bottles are arranged on the slope surface at the top, the rock and soil demarcation, the flood water level, and the middle points of the two sections that separate the slope surface from the above three points. Each bottle was filled with different colored water. When the water-conducting fractures of the overlying strata reached the water bottles during simulated mining, the water in the bottles flows outward through the conducting channel. Subsequently, the degree of damage to the slope will be judged by the development of water-conducting fractures in the overlying strata. Thus, the minimum width of the coal pillar required to prevent the loss of water from a reservoir can be determined.

A DH3816N static strain testing and analysis system is arranged on the mining face, and displacement dial gauges are arranged on the surface to analyze the overburden rock failure characteristics and surface deformation laws during...
mining. The survey lines A, B, C, D, and F are arranged on the surface, rock and soil demarcation, stratification between fine-grained sandstone and lower mudstone, roof of the 4\(^2\) coal mine, and reservoir bank slope surface, respectively. The monitoring scheme is presented in Figure 5.

The mining direction of the coal seam during actual mining is from right to left after the width of the waterproof coal pillar was determined. However, to determine the width of the coal pillar, in this study, the mining direction is considered to be from left to right to determine the width of the coal pillar. Each excavation is 1 cm long, interval time is 3–5 min, and the mining height of the 4\(^2\) coal mine is 3.5 cm. Considering the boundary effect, we set up a 35 cm protective coal pillar on the left side of the model.

### 4.2. Coal Seam Mining Test

During mining, the open-off cut of the 4\(^2\) coal seam is 35 cm on the left side of the model. When the working face advances to 26.0 cm, the goaf collapses and the caving height is observed to be approximately 3.5 cm. When the working face advances to 58 cm, the immediate roof collapses over a large range and the key stratum (27.3 cm of fine-grained sandstone on the roof) partially collapses. The caving zone height is 14.0 cm, the free space is up to 3.5 cm high and 19.5 cm long, and the height and 32.5 cm long, and the caving angle on the mining side is 70°, and the working face pressure is 3.5 cm. Considering the boundary effect, we set up a 35 cm protective coal pillar on the left side of the model.

When the working face advances to 128 cm, the water in the reservoir would flow into the goaf through the abscission layer fractures. This indicates that when the water level reaches or exceeds this layer fractures when the reservoir is full.

When the working face advances to 139 cm, the working face roof undergoes its fourth periodic collapse. Because of the tensile failure of the overburden rock, a vertical downward fracture up to 38.5 cm can be observed from the topsoil to the bedrock above the working face as shown in Figure 6(d). The cumulative displacement of the top point P1 is 30 mm. Meanwhile, many fine transverse abscission layer fractures can be observed in the upper soil layer of the slope surface, and the water in the red water storage bottle at P1 begins to seep into soil. This indicates that water will flow into the slope and goaf through the transverse abscission layer fractures when the reservoir is full.

When the working face advances to 155 cm, the working face roof falls for the fifth time. At this point, all the overburden strata of the working face are broken, the topsoil sinks, and obvious transverse cracks can be observed on the surface. The maximum settlement of the A survey line displacement monitoring point is 2.5 cm. The top point P1 on the slope surface, which is 37.1 cm ahead of the working face, moves toward the goaf, and its displacement is 13 mm, as shown in Figure 6(c). According to the surface movement criterion presented in "Regulations for coal pillar setting and coal mining under pressure in buildings, water bodies, railways and main roadways" [16], the slope surface begins to move when the working face advances to 128 cm.

When the working face advances to 155 cm, the working face roof falls for the fifth time, the topsoil sinks over a large area for the second time, and the step distance is observed to be approximately 30 cm. As shown in Figure 6(e), the strata movement boundary angle decreases to 60°. The tensile failure of the overlying rock leads to a new vertical downward fracture over the working face. Meanwhile, the vertical downward fracture produced earlier gradually closes. The slope body tends to turn toward the goaf, and the abscission layer fractures appear in the middle soil layer, resulting in the seepage of water from the blue water storage bottle. This indicates that when the water level reaches or exceeds this position, the water in the reservoir would flow into the goaf through the abscission layer fractures.

When the working face advances to 221 cm, the reserved width of the coal pillar is observed to be 70 cm. At this point, the entire slope body above the working face begins

### Table 3: Proportion schemes for similar materials of simulated rock strata.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Laterite</th>
<th>Mudstone</th>
<th>Fine-grained sandstone</th>
<th>Mudstone</th>
<th>Fine-grained sandstone</th>
<th>Siltstone</th>
<th>4(^{2}) coal</th>
<th>Fine-grained sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density in prototype (g/cm(^3))</td>
<td>2.208</td>
<td>2.35</td>
<td>2.67</td>
<td>2.35</td>
<td>2.69</td>
<td>2.7</td>
<td>1.28</td>
<td>2.69</td>
</tr>
<tr>
<td>Density in model (g/cm(^3))</td>
<td>1.47</td>
<td>1.57</td>
<td>1.78</td>
<td>1.57</td>
<td>1.79</td>
<td>1.80</td>
<td>0.85</td>
<td>1.79</td>
</tr>
<tr>
<td>UCS in prototype (MPa)</td>
<td>35.4</td>
<td>50.4</td>
<td>35.4</td>
<td>50.4</td>
<td>79.7</td>
<td>71.9</td>
<td>16.43</td>
<td>79.7</td>
</tr>
<tr>
<td>UCS in model (kPa)</td>
<td>230.8</td>
<td>332.2</td>
<td>230.8</td>
<td>332.2</td>
<td>515.4</td>
<td>468.5</td>
<td>107.9</td>
<td>514.4</td>
</tr>
<tr>
<td>Thickness (cm)</td>
<td>25</td>
<td>2.5</td>
<td>5.5</td>
<td>2.5</td>
<td>2.7</td>
<td>2.2</td>
<td>3.5</td>
<td>2.9</td>
</tr>
<tr>
<td>Volume (cm(^3))</td>
<td>250000</td>
<td>25000</td>
<td>45000</td>
<td>55000</td>
<td>273000</td>
<td>22000</td>
<td>35000</td>
<td>295000</td>
</tr>
<tr>
<td>Total mass (kg)</td>
<td>367.5</td>
<td>39.25</td>
<td>80.1</td>
<td>86.35</td>
<td>488.67</td>
<td>39.6</td>
<td>29.75</td>
<td>528.05</td>
</tr>
<tr>
<td>River sand (kg)</td>
<td>174.08</td>
<td>18.59</td>
<td>37.94</td>
<td>40.90</td>
<td>217.19</td>
<td>18.76</td>
<td>12.93</td>
<td>234.69</td>
</tr>
<tr>
<td>Gypsum (kg)</td>
<td>19.34</td>
<td>4.13</td>
<td>12.65</td>
<td>9.09</td>
<td>54.30</td>
<td>6.25</td>
<td>0.65</td>
<td>58.67</td>
</tr>
<tr>
<td>Lime (kg)</td>
<td>174.08</td>
<td>16.53</td>
<td>29.5</td>
<td>36.36</td>
<td>217.19</td>
<td>14.59</td>
<td>3.23</td>
<td>234.69</td>
</tr>
<tr>
<td>Fly ash (kg)</td>
<td>36.7</td>
<td>39.2</td>
<td>8.0</td>
<td>8.6</td>
<td>48.9</td>
<td>4.0</td>
<td>3.0</td>
<td>52.8</td>
</tr>
</tbody>
</table>

**Note:** The table above shows the proportion schemes for similar materials of simulated rock strata. The parameters include density in prototype and model, uniform compressive strength (UCS), thickness, sand : gypsum : lime : fly ash, volume, total mass, river sand, gypsum, lime, and fly ash. **Density in model:** 2.69 g/cm\(^3\), **Density in prototype:** 1.79 g/cm\(^3\), **UCS in model:** 514.4 MPa, **UCS in prototype:** 514.4 MPa, **Thickness:** 70°.
Figure 5: The similar-material physical model monitoring scheme.

Figure 6: Continued.
dumping and rotating, and the draw displacement angle reduces to 58°, as shown in Figure 6(f). A vertical fracture gradually develops in the overlying strata ahead of the working face. Many abscission layer fractures appear in the reservoir bank slope, and slip dislocation occurs between different lithologic layers, resulting in serious slope failure. This suggests that many abscission layer fractures and vertical fractures would occur in the reservoir bank slope when the actual coal seam advances to 221 m, destroying the slope and weakening the antiseepage function, which would result in a serious water inrush accident.

When the working face advances to 246 cm, the reserved coal pillar width is 45 cm. Because of the combined action of the collapse of the overlying strata and reservoir slope free surface and the development of deep vertical fractures, the overlying strata experience cutoff caving and many abscission layer fractures appear in the slope body. The upper part of the slope is completely unstable and undergoes an obvious slip displacement, whereas the lower part of the slope tends to slide toward the reservoir, as shown in Figure 6(g). This indicates that mining would result in the destruction of the slope.

5. Numerical Simulation of Coal Seam Mining

The numerical simulation model was built using FLAC3D and had a computational area of 500 m (length) × 0.2 m (width) × 1 m (height). The values of the physical and mechanical parameters of each layer in the model have been presented in Table 2. The slope angle was 40°, and the 4−2 coal mine was 67 m deep and 279 m long. The open-off cut is 100 m from the model’s left edge and 179 m from the reservoir bank in the horizontal direction. The mining direction in the model was from left to right, and the water level of the Changjiagou Reservoir was at its highest level of 27 m. We marked several monitoring points on the slope surface to
analyze and compare the calculation results. The displacement monitoring points P1, P2, and P3 are located at the top point, the rock and soil demarcation, and the highest water level, respectively. Four pore pressure monitoring points, i.e., A1, B1, C1, and D1, were laid at the coal seam roof level distanced from the reservoir bank at 89, 79, 69, and 59 m, respectively. Four additional pore pressure monitoring points, i.e., A2, B2, C2, and D2, were laid at the corresponding floor levels of the first four points, respectively. The layout of these monitoring points on the model is presented in Figure 7.

6. Analysis and Discussion

6.1. Analysis of the Overlying Strata Failure Characteristics. As shown in Figure 6, when the working face advances to 128 m, the vertical displacement of the slope vertex is 13 mm, indicating that the slope vertex enters the surface subsidence basin and that the slope begins to be affected by coal seam mining. Here, the strata movement boundary angle is 61°. When the working face advances to 155 m, the strata movement boundary angle is 60°, whereas the strata movement boundary angle is 58° when it advances to 221 m. Furthermore, when the working face advances to 246 m, the strata movement boundary angle is 58° when it advances to 221 m. The results demonstrate that when the working face is close to the reservoir, the strata movement boundary angle decreases and the moving range of the overlying stratum increases with the reduced width of the waterproof coal pillar. This is because the overlying strata lose support and fall into the goaf due to coal seam mining, and the strata on both the sides lose lateral support and move to the middle loose zone. These processes cause movement of the overlying strata and surface subsidence. When the working face advances to near the bank slope, the overlying strata fall, and the layers on both the sides loosen toward the middle zone. Here, the bank slope is an airborne free surface, which leads to a smaller lateral restraint on the right side strata above the goaf when compared with that observed without considering the slope. Thus, the loosening stratum range on the right side increases, and the strata movement boundary angle decreases.

Figure 8 shows the horizontal displacement variation curves for three monitoring points (P1, P2, and P3) on the reservoir bank slope surface with the width of the waterproof coal pillar being obtained by the physical simulation test and numerical simulation. The curves obtained by these two simulations show consistent variation trends. When the waterproof coal pillar is wide, the influence of mining on the slope is considerably small. However, when the width of the waterproof pillar decreases to 163 m, the monitoring point P1 begins to move to the goaf side, and the horizontal displacement gradually increases as the coal pillar width decreases. As the width of coal pillar width continues to decrease, the horizontal displacement of the point P1 initially decreases and subsequently increases, indicating that point P1 produces a reverse displacement and begins to move toward the reservoir. Further decreases of the of coal pillar width produce horizontal displacement with respect to the monitoring points P2 and P3. Additionally, the horizontal displacements of the points P1, P2, and P3 drastically increase as the coal pillar width decreases. In this case, the slope tends to slip toward the reservoir, and further mining will lead to an integral slip of the bank slope.

Figure 9 shows the vertical displacement curves of the monitoring points P1, P2, and P3 on the reservoir bank slope based on the waterproof coal pillar width obtained by the physical simulation test and numerical simulation. The curves obtained by the two simulations show consistent variation trends. Mining exhibits little influence on the slope when the protective pillar is wide. When the width of the waterproof coal pillar decreases to a certain value, vertical displacement initially occurs at P1 at the top of the slope, indicating that coal seam mining results in the loosening of the overlying rock and soil layers to the goaf side and downward movement due to the loss of support. As the width of the waterproof coal pillar decreases, the disturbances of the overlying strata become more obvious and the vertical displacement of P1 increases gradually. With further decreases in the coal pillar width, the vertical displacements of the three monitoring points drastically increase, indicating that the slope begins to slip toward the reservoir and loses stability.

Figure 10 shows the distribution curve of the vertical stress on the floor of the coal seam. When the working face advances to 139 m, the overlying strata do not topple and slip and the vertical stress distribution on the floor is consistent with that of the conventional mining conditions. When the working face advances to 155 m, the overlying strata’s center of gravity shifts, the vertical stress redistributes, and the vertical stress distribution curve presents a double peak characteristic.

The following can be obtained by analyzing Figures 8–10 and the phenomenon in a physical model test using similar materials:

1. When mining the working face, the overlying strata lose support and fall to the goaf, and the rock and soil mass on both the sides move to the middle loose zone. When the working face is close to the reservoir bank slope, the overlying strata above the working face collapse, and the reservoir bank slope loses support, resulting in the dumping and slipping of the slope to the goaf. As the working face advances, downward vertical fractures occur in front of the working face due to the tensile failure of the overlying strata. Due to the existence of the slope of the reservoir bank, the overlying strata lose their horizontal constraints on the slope side of the reservoir bank and the abscission layer fractures caused by mining develop rapidly. When the vertical downward fractures connect with the abscission layer fractures, the slope is cut into blocks. Furthermore, the slope slips to the reservoir when the shear strength of the destroyed strata is reduced and the segmented slope’s sliding force is greater than the interlayer antisliding forces. Thus, the reservoir bank slope presents the failure modes of dumping and
slipping initially with respect to the goaf and subsequently with respect to the reservoir.

(2) Due to coal seam mining, the slope vertex initially moves to the side of the goaf. When the working face is close to the reservoir bank slope, the slope is cut into blocks with both downward vertical and abscission layer fractures, and the slope loses lateral support and slips to the reservoir. Here, the direction of the slope vertex horizontal displacement turns to the reservoir, and the vertical displacements of several monitoring points on the slope drastically increase. Therefore, the conditions by which the direction of the slope vertex horizontal displacement turns to the reservoir or the vertical displacements of the monitoring points on the slope surface drastically increase can be used to evaluate when the slope begins to slip toward a reservoir.

6.2. Analysis of the Variation Characteristic of Pore Pressure. Figure 11 shows the pore pressure variation curves for the monitoring points on the roof and floor of a coal mine with the width of the waterproof coal pillar when the reservoir water level is 14 m above the coal seam roof. These curves were obtained from the result of the numerical simulation model. The monitoring points A1 and A2 have pore pressures of 0, whereas the monitoring points B1, C1, D1, B2, C2, and D2 have pore pressures greater than 0 when the width of the waterproof coal pillar is large and the reservoir bank slope is not affected by mining. This indicates that the saturation line lies between A1 and B1 on the roof and between A2 and B2 on the floor. When the protective coal pillar width is 89 m, the pore pressures of B1 and B2 decrease to 0, whereas the pore pressures of C1, D1, C2, and D2 are greater than 0. This indicates that the working face becomes a free water surface at that point. Therefore, when the reservoir’s water level is 27 m, the reserved width of the coal pillar should
not be less than 89 m to ensure the protection of the goaf from a flooding accident.

6.3. Judgment Conditions of the Critical Width of the Waterproof Coal Pillar. Based on the simulation results, comprehensive judgment conditions are proposed with respect to the critical width of the waterproof coal pillar as follows:

(1) Based on the variation characteristics of the horizontal and vertical displacements of the monitoring points on the reservoir bank slope surface, the width of the waterproof coal pillar when the slope vertex produces reverse horizontal displacement and many monitoring points produce sharp vertical displacements can be considered to be the critical width for protecting the reservoir bank slope from instability sliding, which is recorded as \( L_1 \).

(2) Based on the variation characteristics with respect to the pore pressure of the monitoring points on the roof and floor of coal mine, the width of the waterproof coal pillar when the pore water pressure on the roof and floor of coal seam suddenly decreases to 0 can be considered to be the critical width for protecting the goaf from a flooding accident, which is recorded as \( L_2 \).

(3) The critical width of the waterproof coal pillar is:

\[
L = \text{MAX}(L_1, L_2)
\]

Based on the above analysis using the physical simulation test and numerical simulation, \( L_1 \) is 96 m, \( L_2 \) is 89 m, and the critical coal pillar width is 96 m when the reservoir’s water level is 27 m.

Through the aforementioned analysis, the critical coal pillar width is 96 m using simulation, whereas it is 107.51 m using the theoretical method. The results indicate that the theoretical method required for determining the width of the waterproof coal pillar is reasonable to ensure the safety of coal seam mining.

7. Conclusion

To determine a reasonable reserved waterproof coal pillar width for the mining of a shallow coal seam located close to a reservoir, we adopted the methods of theoretical analysis, physical simulation using similar materials, and numerical simulation to study the overburden strata mining failure features and the deformation mechanism of the reservoir bank slope. The main conclusions can be given as follows:

(1) The saturation line of the slope was determined, and the formula for calculating the coal seam width with respect to the saturation line was deduced by simplifying the saturation line of the reservoir bank slope into an upper wedge section and a main seepage section. Based on the failure characteristics of the coal seam roadway, the waterproof coal pillar was divided into a mine-pressure-influenced zone, an effective waterproof zone, and a water-level-influenced zone. Furthermore, a theoretical method was proposed for determining the width of the waterproof coal pillar.

(2) The failure modes of the reservoir bank slope in case of coal seam mining were studied with a physical simulation test using similar materials. The results demonstrated that when the working face becomes close to the reservoir, the reservoir bank produces vertical downward and transverse abscission layer fractures, and the slope is divided into blocks by these fractures. The formation of the transverse abscission layer fractures causes the topsoil to initially produce horizontal displacement with respect to the reservoir. When the vertical downward fractures completely connect with the transverse abscission layer fractures in the topsoil, the divided topsoil slips toward the reservoir, which causes the instability failure of the slope.
(3) To prevent instability failure in the reservoir bank slope and the gushing of water in the goaf, evaluation conditions have been proposed to determine the critical width of the waterproof coal pillar. The maximum width of the coal pillar in which the top point on the slope surface experienced reverse horizontal displacement and several key points produced sharp vertical displacements or when the pore pressure in the coal seam roof and floor suddenly changed to 0 was considered to be the critical width.

(4) The theoretical result was verified using simulation analysis, indicating that the theoretical method can be used to determine the width of the waterproof coal pillar of the coal seam located close to a reservoir. In addition, the results provide important references for the safety mining of the coal seam located close to a reservoir, which are considerably significant to conserve coal resources, improve the recovery rate, and ensure the normal and safe operation of the reservoir during the coal mining process.

(5) In this paper, the reasonable width of the waterproof coal pillar was researched using theoretical analysis, physical simulation using similar materials, and numerical simulation. In the future, the field tests will be conducted in the Zhangjiamao mine to further verify the results. Furthermore, the width of the waterproof coal pillar of the coal seams under the reservoir will also be studied.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (Project nos. 41702346 and 11872299), Research Fund of Shaanxi Education Department (Project no. 17JK0502), and Cultivation Fund of Xi’an University of Science and Technology (Project no. 201729).

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