

Article

The Influence of Water Accumulation in Open Pits on the Stability of Boundary Coal–Rock Pillars

Junhai He ¹, Cunjin Lu ^{1,*}, Yongqiang Zhang ^{2,3}, Hui Zhao ¹ and Jinpeng Xu ¹

¹ School of Resources and Geosciences, China University of Mining and Technology, Xuzhou 221116, China; ts24010087a31@cumt.edu.cn (J.H.); tb23010022a41@cumt.edu.cn (H.Z.); xjp319@126.com (J.X.)

² School of Mines, China University of Mining and Technology, Xuzhou 221116, China; db23020058p41@cumt.edu.cn

³ Huoluowan Coal Mine, Inner Mongolia Shendong Tianlong Group Co., Ltd., Ordos 710021, China

* Correspondence: lcjcumt@cumt.edu.cn; Tel.: +86-13813457371

Abstract

To reveal the influence of water accumulation in open pits on the stability of boundary coal–rock pillars, this study investigates a boundary coal–rock pillar between an underground coal mine and an adjacent open pit in western China. Coal–rock physical property tests, hydrochemical analysis, permeability tests, and theoretical calculations of water-resisting coal–rock pillars were conducted to examine seepage channel formation, physical property changes, and stability evolution under long-term water accumulation. The results show that the mechanical strength of coal and rock specimens decreases under the saturated state. The uniaxial compressive strength of rock specimens decreases by 8.75–50.64%, while that of No.2^{−2} and No.3^{−1} coal specimens decreases by 17.72% and 25.01%, respectively. The tensile strength decreases by 24.59–59.11%, and the shear strength decreases by 4.36–45.96%. The hydraulic conductivity of intact specimens is mostly 10^{−4}–10^{−3} m/d, whereas that of fractured specimens increases to 10^{−3}–10^{−2} m/d. The calculated width of water-resisting coal pillars increases by 19.7–21.9% under long-term water accumulation. Long-term water accumulation in the open pit changes the external hydraulic boundary of the boundary coal–rock pillar, allowing water to migrate inward along bedding planes, joints, primary fractures, mining-induced fractures, and coal seam pores. This process promotes the connection of pre-existing pore–fracture structures and seepage channel formation, weakens particle cementation and structural-plane shear resistance, and reduces the structural integrity, bearing capacity, and water-resisting capacity of the coal–rock pillar. Therefore, the stability deterioration of boundary coal–rock pillars is a continuous process involving channel formation, sustained seepage, strength degradation, enhanced pore–fracture connectivity, permeability enhancement, and further stability reduction.

Keywords: water accumulation in open pits; boundary coal–rock pillar; seepage channel; strength degradation; effective water-resisting and bearing zone



Academic Editor: Paula M. Carreira

Received: 22 June 2026

Revised: 9 July 2026

Accepted: 14 July 2026

Published: 18 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Coal resources occupy a dominant position in China's energy structure. With the continuous exploitation of coal resources, both the depth and intensity of mining have increased, and hydrogeological conditions have become increasingly complex. As a result, mine water hazards have gradually become one of the key factors restricting the safe and efficient production of coal mines. Among these hazards, water inrush has long been a

major focus of mine water hazard prevention and control because of its sudden occurrence and severe consequences [1–5].

During coal mining, lateral water bodies formed in open pits or abandoned goafs may exert sustained hydraulic pressure and induce water–rock interaction on adjacent working faces and boundary coal–rock pillars. Water can migrate into the interior of boundary coal–rock pillars through pores, joints, bedding planes, and mining-induced fractures, thereby altering their mechanical properties, seepage characteristics, and structural integrity, ultimately leading to strength degradation [6]. Under the long-term influence of water accumulation, the bearing capacity and water-resisting capacity of water-resisting coal–rock pillars may gradually decrease, and in severe cases, this may induce coal–rock pillar instability or even water inrush accidents [7–9]. For example, in May 2013, the Huhewusu Open-pit Coal Mine in Inner Mongolia, due to the mining of the boundary coal pillar with the Ulan Mulun River, caused the river water to be poured into the mining pit and then poured into the flooded well of the Huhewusu underground coal mine, resulting in the adjacent Bulianta Coal Mine 2^{–2}-coal-seam two-panel goaf being affected and forced to stop production [10].

In recent years, considerable progress has been made in studies on coal mine goafs and water-resisting coal pillars. Regarding coal pillar width and stability, previous studies have investigated the failure width of coal pillars and the stability of strip coal pillars through theoretical analysis, field monitoring, and numerical simulation, and have further discussed the reasonable width of water-resisting coal pillars [11,12]. In terms of coal–rock damage under water action, researchers have also examined the effects of immersion duration, water pressure, hydrochemical conditions, and moisture state on the strength and pore–fracture structure of coal samples [13–19]. With respect to seepage channel formation, several studies have analyzed fracture connection, permeability evolution, and the formation mechanisms of water hazard channels from the perspectives of stress–seepage coupling, lateral seepage–axial loading, coal seam water-injection seepage, and hydro-mechanical coupling [2,4,20–22]. In addition, some studies have shown that water-level recovery and fluctuation in open pits can alter pore water pressure and the stress conditions of structural planes in rock masses, thereby exerting a sustained influence on the stability of adjacent rock masses [23,24].

Although the above studies have made important progress in theoretical analysis, experimental simulation, and numerical methods, several limitations remain. Most existing studies have focused mainly on water accumulation in underground mine goafs, while relatively limited attention has been paid to the stability of boundary coal–rock pillars under lateral water accumulation from open pits. In addition, previous research has generally emphasized a single mechanism, such as stress or seepage, whereas the changes in the physical properties of coal–rock pillars, the development of seepage channels, and the stability evolution mechanism under stress–seepage interaction remain insufficiently understood. Although there have been cases in history where open-pit water has caused mine water inrush to eventually flood the well, in previous studies, there has been basically no related research on open-pit water and underground mining.

Based on this background, this study takes the boundary coal–rock pillar between an underground coal mine and an adjacent open pit in a western mining area of China as the research object. Coal–rock physical property tests, hydrochemical analysis, permeability tests, and theoretical calculations are conducted to investigate the strength and seepage characteristics of coal and rock under natural and saturated states. This study links water accumulation in the open pit, seepage channel development, and stress–seepage interaction, and establishes an analytical framework of “water source–seepage channel–coal–rock pillar–working face.” Based on this framework, the influence of water accumulation in the

open pit on the stability of the boundary coal–rock pillar is analyzed, and the development characteristics and formation mechanism of seepage channels in the boundary coal–rock pillar under water accumulation are discussed. The influence mechanism of water accumulation on the stability of boundary coal pillars in open-pit mines is revealed, and the safety of the coal pillar is evaluated. The research results can provide a reference for the safety evaluation and water disaster prevention and control of boundary coal pillars under the condition of lateral water accumulation in similar open-pit mines.

2. Overview of the Study Area

2.1. Geological Conditions

The mine is located in Inner Mongolia Autonomous Region, China, and its eastern minefield boundary is adjacent to an open pit, representing a typical adjacent mining area with an “open pit–underground mine” configuration (Figure 1). The minefield covers an area of 13.2021 km². The main minable seams are the No. 2⁻² and No. 3⁻¹ coal seams of the Jurassic Yan’an Formation; the thickness range of the No. 2⁻² coal seam is 0.93~6.35 m, with an average thickness of 4.83 m, while the thickness range of the No. 3⁻¹ coal seam is 0.85~4.67 m, with an average thickness of 3.57 m. The geological structure of the mining area is generally simple, characterized by a broad and gentle monocline. The strata strike N25° W, dip toward S65° W, and have a dip angle of 1–3°. The main aquifers in the area include the Quaternary loose-rock pore aquifer, the Cretaceous Zhidan Group clastic-rock pore–fracture aquifer, and the Jurassic sandstone fractured confined aquifer. The main aquicludes are Pleistocene Malan loess, Jurassic mudstone, and sandy mudstone.

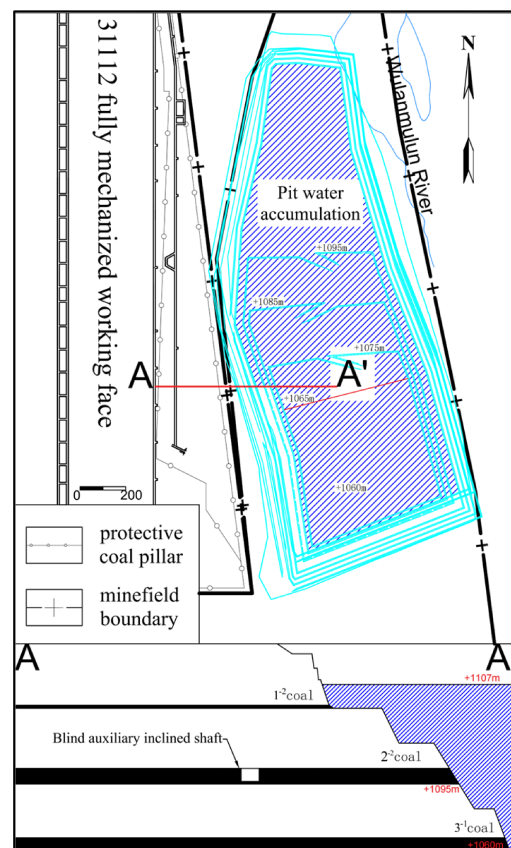


Figure 1. Schematic plan of mining and stripping engineering in the open pit. The geological cross-section was constructed along the A–A' profile line.

2.2. Water Accumulation in the Adjacent Open Pit

After the extreme rainfall event on 21 July 2012, the water level of the nearby river rose sharply. At that time, small-mine roadways in the No. 2⁻² coal seam existed on the eastern side of the open pit. As the water level and hydraulic pressure in these small-mine roadways increased, the accumulated water broke through the protective coal pillar along the sidewall of the open pit, allowing a large volume of river water to flow into the open pit through the small-mine roadways. Since then, a large amount of water has remained accumulated in the open pit. After water accumulation formed in the open pit, no dedicated drainage facilities were installed. The accumulated water was mainly controlled by rainfall recharge, evaporation, and seepage conditions in the surrounding strata, and generally remained in a relatively long-term stagnant state.

Since the open pit has accumulated water, long-term water-level monitoring has been carried out. According to the existing data, the accumulated water in the pit accepts the stable supply of nearby rivers, and the water level has been maintained at about +1107 m for a long time. The water level can reach +1109.716 m in the rainy season. The elevation of the stripping floor at the southernmost end of the open pit is +1060.1 m, and the average water depth is 49 m. The flooded areas are mainly 2⁻² coal, 3⁻¹ coal and medium sandstone and sandy mudstone (Figure 1), which are close to the position of the boundary coal–rock pillar in the eastern part of the study area, and have the hydrogeological conditions for lateral seepage to the underground mining space.

2.3. Water Seepage Status and Boundary Coal Pillar Exploration

After the water accumulation in the open-pit mine, the seepage phenomenon occurred in the coal passing section of the dark auxiliary inclined shaft. After curtain grouting treatment, the measured seepage volume was still 7~25 m³/h; due to the influence of long-term water accumulation in the return air crossheading of the 31112 working face, water spray occurs in the roadway, and the water inflow reaches 45.4 m³/h. After curtain grouting treatment, the measured seepage volume is still 7.7 m³/h. This shows that there may be a certain hydraulic connection between open-pit water and underground mining space.

In order to determine the situation of the eastern boundary coal pillar, geophysical exploration, drilling and surface horizontal hole exploration have been carried out. The exploration results show that the coal seam in the exploration area of the directional drilling in the eastern boundary of the minefield is complete, and the cross-border situation of the open pit is not detected. The minimum distance between 2⁻² coal and the eastern boundary coal pillar of the mine is 84.9 m, and the minimum distance between 3⁻¹ coal and the eastern boundary coal pillar of the mine is 74 m.

3. Materials and Methods

3.1. Exploration of the Boundary Coal–Rock Pillar

Due to the need to study the long-term water accumulation in different strata of coal–rock pillars, we set up sampling boreholes in the boundary coal–rock pillar area adjacent to the open-pit water accumulation at the end of 2024, and obtained coal–rock samples by means of roadway geological borehole coring. The sampling position is selected in the boundary coal pillar area, which can better reflect the actual state of the coal and rock mass under long-term water accumulation. The sampling depth range is 90~270 m, covering 2⁻² coal, 3⁻¹ coal and its roof and floor strata, including sandy mudstone, siltstone, fine sandstone and medium sandstone. A core that meets the standard sample processing size and has no macroscopic cracks is selected. The effective samples of each lithology are as follows (Table 1). The number outside the brackets represents the number of test samples, and the number inside the brackets represents the number of valid samples.

It should be pointed out that an effective sample is a specimen that passes the corresponding test and obtains a reliable test value. Specimens that were broken before loading, were broken during the saturation process, or had a lack of effective test records were not included in the statistical calculation.

The natural sample is obtained by on-site coring. After obtaining the core, the surface of the rock sample is tightly wrapped with a moisturizing film, and the sample is then placed in a plastic packaging belt and transported to the laboratory to be processed into a standard size.

Table 1. Number of valid specimens used for mechanical tests under natural and saturated conditions.

Lithology	Natural Specimens for Compressive Test	Saturated Specimens for Compressive Test	Natural Specimens for Shear Test	Saturated Specimens for Shear Test	Natural Specimens for Tensile Test	Saturated Specimens for Tensile Test
Siltstone	16 (10)	5 (5)	12 (7)	5 (5)	14 (9)	5 (5)
Fine sandstone	11 (4)	3 (3)	12 (11)	7 (7)	11 (7)	5 (5)
Medium sandstone	35 (26)	11 (11)	25 (22)	15 (15)	32 (28)	15 (15)
Sandy mudstone	11 (10)	6 (6)	10 (4)	4 (4)	11 (8)	5 (5)
2 ^{−2} coal	4 (4)	2 (2)	4 (4)	2 (2)	3 (3)	3 (3)
3 ^{−1} coal	4 (4)	2 (2)	6 (6)	3 (3)	3 (3)	3 (3)
Total	81 (58)	29 (29)	69 (54)	36 (36)	74 (58)	36 (36)

The standard sample was placed in a vacuum drying oven, vacuumized to -0.09 MPa and kept for 2 h, and then immersed in deionized water for 48 h until the quality was basically stable, so that the sample reached the saturation state required for the test, and it was placed in ionic water to maintain saturation before the test.

Testing began immediately after the completion of sample preparation.

Mechanical property test specimens: The uniaxial compressive test specimen has a diameter of 50 mm and a height of 100 mm; the diameter of the shear strength test specimen is 50 mm and its height is 50 mm. The tensile strength test specimen (Brazil splitting method) has a diameter of 50 mm and a height of 25 mm. The non-parallelism at both ends of the specimen is $\leq \pm 0.05$ mm, and the perpendicularity deviation between the end face and the axis is $\leq \pm 0.25^\circ$.

Permeability test specimens: Diameter 25 mm, height 50 mm, flat end face. A complete specimen in this paper refers to a specimen without penetrating cracks or obvious damage at either end before the test; fractured specimens refer to specimens that can have identified penetrating fractures and still maintain their overall structure after prefabrication or loading. They are used to simulate the seepage state after the weak structural plane inside the coal–rock column is connected (Figure 2). The artificial cutting method is used to prefabricate a crack with a width of about 1 mm in the complete coal–rock specimen, and the crack direction is arranged along the axial direction of the specimen. It is used to simulate the influence of joints and mining-induced fissures in coal and rock masses on seepage capacity. The fractured specimen is only used for comparative analysis of the permeability difference between the intact and fractured states [25].



Figure 2. Representative photos of intact specimens and fractured specimens in permeability test. (a) Complete specimens. (b) Fractured specimens.

The coal–rock mechanical property tests included uniaxial compressive strength, tensile strength, and shear strength tests. All tests were conducted using an MTS815 electro-hydraulic servo rock mechanics testing system (China University of Mining and Technology, Xuzhou, China). The processing and testing processes of coal and rock specimens are in accordance with the national standard of the People’s Republic of China “Standard for test methods of engineering rock mass” (GB/T50266-2013) [26], and refer to the water conservancy and hydropower industry standard of the People’s Republic of China “Water conservancy and hydropower engineering rock test procedures” (SL/T 264-2020) [27]. The uniaxial compressive strength test was performed at a loading rate of 2 kN/s to determine the axial bearing capacity of coal and rock specimens with different lithologies. The tensile strength test was conducted using the Brazilian splitting method at a loading rate of 0.5 kN/s to characterize the resistance of coal and rock specimens to tensile failure. The shear strength test was carried out using shear fixtures with angles of 40°, 50°, and 60° at a loading rate of 1 kN/s, and the cohesion and internal friction angle were calculated based on the Mohr–Coulomb strength criterion.

The permeability test is completed with an LDY-1 high-temperature and high-pressure flow experiment instrument (Figure 3) (China University of Mining and Technology, Xuzhou, China). Combined with MT224-1990 “Standard for determination of permeability coefficient of coal and rock” [28] and the method for using the flow experiment instrument, a seepage experiment on rock is carried out, in which the seepage medium is deionized water.

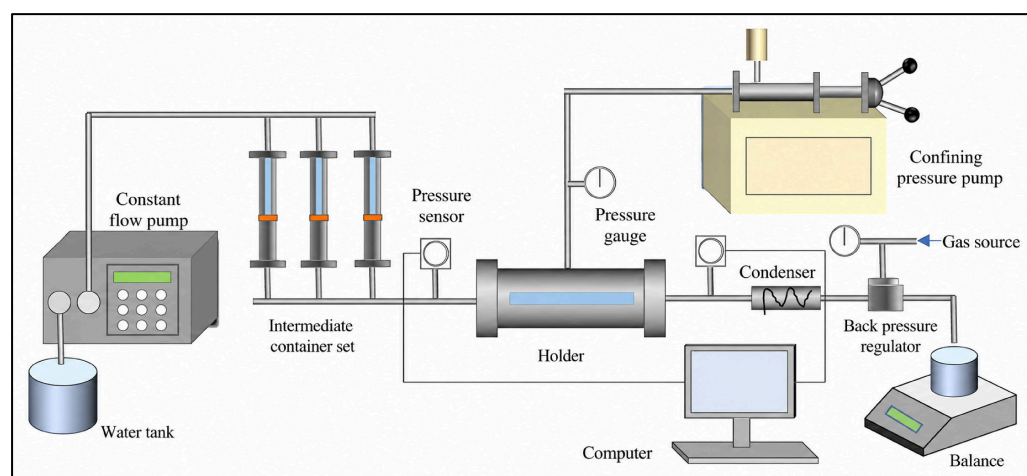


Figure 3. Schematic diagram of the LDY-1 high-temperature and high-pressure flow apparatus.

During the test, the standard sample is first put into the core gripper to make the axis direction of the sample consistent with the seepage direction, and the gripper is sealed and fixed to ensure that the fluid mainly flows along the pores and fissures inside the sample during the test. Then, the set pressure is applied to the sample through the loading system to simulate the formation pressure conditions of the coal–rock mass. At the same time, the temperature is adjusted according to the test requirements to keep the test environment stable. After the pressure and temperature reach the set value and remain stable, clean water is injected into the inlet end of the sample to make the water pass through the sample under the action of stable pressure difference.

During the seepage process, the pressure sensor is used to record the pressure difference between the inlet and outlet of the sample in real time, and the water flow through the sample is collected at the outlet end for a certain period of time. After the seepage process reaches a relatively stable state, the seepage time, water output or water quality, sample size and inlet and outlet pressure difference are recorded. In order to reduce accidental error, each group of samples is continuously observed after the pressure is stable, and the data on the stable seepage stage are selected for calculation. Finally, the permeability coefficient of the sample is calculated according to Darcy's law to characterize the permeability of different coal and rock samples.

The complete specimens and fractured specimens were tested, respectively, and long-term seepage observation was carried out to analyze the permeability characteristics of different coal strata under the conditions of fracture development and continuous seepage. The permeability test results are used to determine the water conductivity and potential seepage channel development conditions of different lithological layers in the boundary coal pillar.

3.2. Water Quality Analysis

According to the general provisions of “coal mine water quality analysis” MT/T 894-2000 [29], we collected three groups of representative water samples in June 2024, including water samples from the closed drainage roadway of the 31106 working face, water samples from the return air channel of the 31112 working face and water samples from open-pit mining, and carried out water quality testing in June of the same year.

The test indicators included major ions (K^+ , Na^+ , Ca^{2+} , Mg^{2+} , Cl^- , SO_4^{2-} , HCO_3^- , and CO_3^{2-}), pH, total dissolved solids (TDSs), total hardness, and total alkalinity. The test results were analyzed by comparing the ionic composition, mineralization degree, and other hydrochemical characteristics of the water samples, so as to identify the source composition of seepage water in the 31112 working face [30].

3.3. Theoretical Analysis of Coal–Rock Pillar Stability

Water action can alter the strength parameters, fracture structure, and energy evolution characteristics of coal–rock pillars, thereby further affecting their bearing capacity and stability [6,10,11]. To reveal the influence of water accumulation in the open pit on the stability of the boundary coal–rock pillar, this study introduces the theory of water-resisting coal–rock pillar design based on coal–rock mechanical property tests, permeability tests, and hydrochemical analysis, and analyzes the stability response of the boundary coal–rock pillar under long-term water accumulation. According to the tensile strength test results of the No. 2^{−2} and No. 3^{−1} coal seams, the theoretical widths of the water-resisting coal–rock pillar under the natural state and after water action were calculated, respectively. The variations in the required coal–rock pillar width under different water-level conditions were then compared by considering parameters such as coal seam thickness, actual water head, and safety factor.

Meanwhile, combined with the changes in coal–rock strength, the enhanced permeability of fractured specimens, and the hydrochemical similarity of water samples, the effects of water accumulation in the open pit on the bearing capacity, water-resisting capacity, and seepage channel formation of the boundary coal–rock pillar were comprehensively analyzed. This provides a basis for the subsequent discussion of the stability evolution mechanism.

4. Results

4.1. Coal–Rock Physical Property Test Results

In order to analyze the physical properties of boundary coal–rock pillars and their surrounding rocks under the action of water accumulation in open-pit mines, uniaxial compression, tensile, shear and permeability tests were carried out on coal–rock samples with different lithologies. The numbers of effective specimens of each lithology in the natural state and saturated state are shown in Table 1. The test results are expressed as the average of the effective specimens. The results are shown in Figure 4 and Table 2 (the original test data are shown in Appendix A, Tables A1–A6). Because the coal–rock samples are taken from different horizons and buried depths, the specimens themselves have a certain heterogeneity, and the numbers of effective specimens of some lithologies in the natural state and the saturated state are not completely consistent. Therefore, this paper mainly uses the average value and deterioration rate for descriptive comparative analysis.

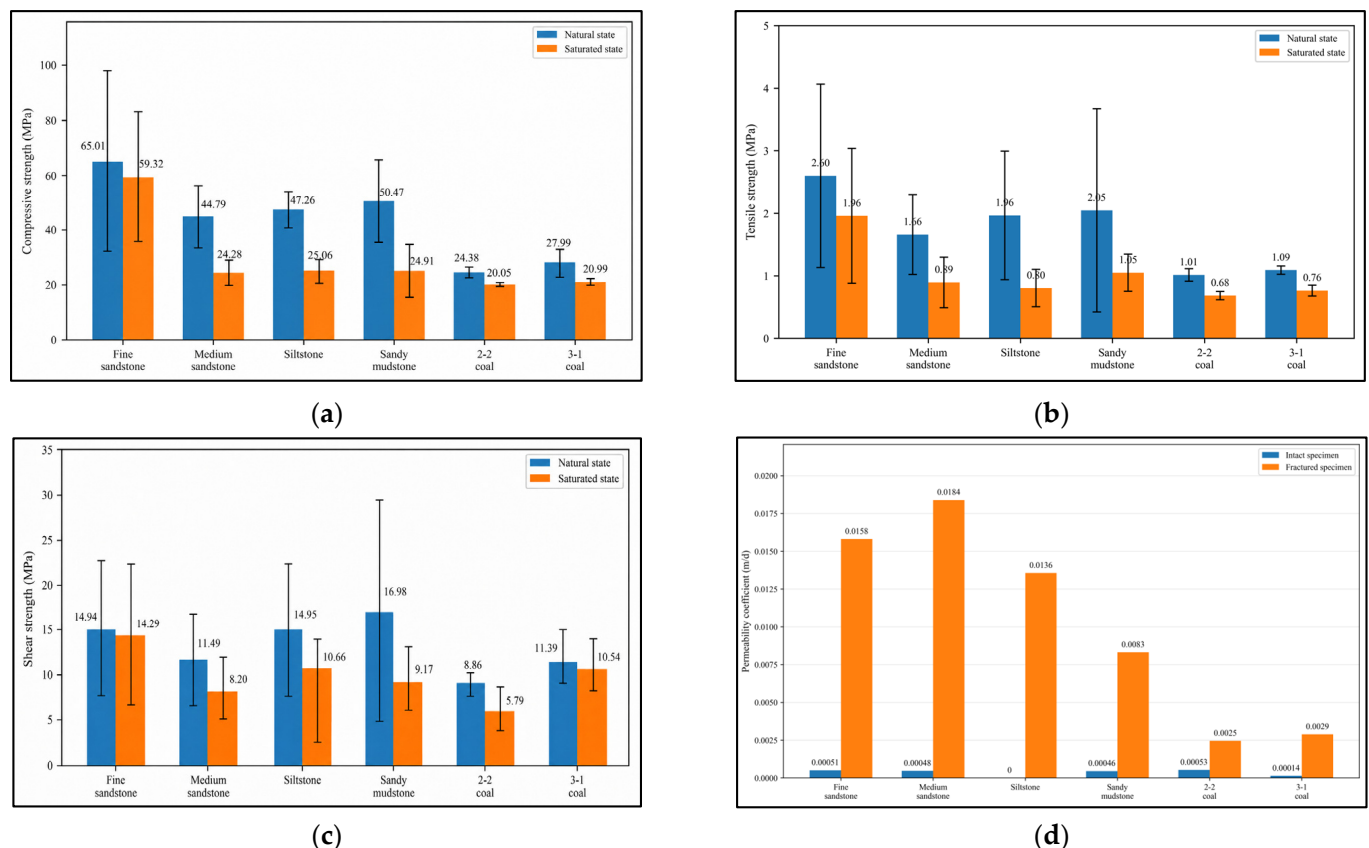


Figure 4. Physical property test results of coal and rock specimens. (a) Compressive strength; (b) tensile strength; (c) shear strength; (d) permeability test.

Table 2. Deterioration rates of mechanical properties of different lithologies.

Lithology	Compressive Deterioration Rate (%)	Tensile Deterioration Rate (%)	Shear Deterioration Rate (%)
Fine sandstone	−8.75	−24.59	−4.36
Medium sandstone	−45.80	−46.13	−28.6
Siltstone	−46.96	−59.11	−28.68
Sandy mudstone	−50.64	−48.71	−45.96
2 ^{−2} coal	−17.72	−32.57	−34.56
3 ^{−1} coal	−25.01	−29.97	−7.53

In order to characterize the variation range in physical and mechanical indexes of coal and rock samples under the natural state and saturated state, this paper uses the degradation rate R to quantitatively describe the changes in uniaxial compressive strength, tensile strength and shear strength. The calculation formula is as follows:

$$R = \frac{X_s - X_n}{X_n} \times 100\% \quad (1)$$

In the formula, R is the deterioration rate, %; X_n is the average value of physical and mechanical indexes of coal and rock samples in the natural state; X_s is the average value of the corresponding index in the saturated state. The larger the value of the deterioration rate, the more obvious the degree of deterioration of the specimen by saturation. The deterioration rate in this paper is used to describe the relative variation range in physical and mechanical properties of coal and rock samples in the natural state and saturated state.

It can be seen from Figure 4a–c that the mechanical strength of coal and rock samples in the saturated state is generally lower than that in the natural state, although the degree of deterioration varies among different lithologies and test types. In terms of uniaxial compressive strength, all coal and rock samples show a decreasing trend after saturation. The deterioration rate of rock samples ranges from −8.75% to −50.64%, among which medium sandstone, siltstone, and sandy mudstone show relatively large reductions, with deterioration rates of −45.80%, −46.96%, and −50.64%, respectively. The uniaxial compressive strengths of 2^{−2} coal and 3^{−1} coal decrease by −17.72% and −25.01%, respectively. In terms of tensile strength, all samples also show strength deterioration under the saturated state, with deterioration rates ranging from −24.59% to −59.11%. Among them, siltstone exhibits the most significant reduction, with a deterioration rate of −59.11%. In terms of shear strength, the shear strength of all lithologies decreases after saturation, with deterioration rates ranging from −4.36% to −45.96%. Sandy mudstone shows the largest shear strength deterioration, while 3^{−1} coal shows the smallest reduction. Overall, the results indicate that saturation has a weakening effect on the mechanical properties of the tested coal and rock samples.

The permeability coefficient is an important parameter to characterize the permeability of coal and rock masses. In this paper, according to Darcy's law, under the condition of stable seepage, the permeability coefficients of different coal–rock samples are calculated. The calculation formula is as follows:

$$K = \frac{Q}{AI} = \frac{Q}{A \frac{\Delta H}{L}} = \frac{QL}{A \Delta H} = \frac{QL}{A \frac{\Delta P}{\rho g}} = \frac{\Delta m L g}{t A \Delta P} \quad (2)$$

In the formula, Q is the water inflow, ml/min; K is the permeability coefficient, m/d; A is the cross-sectional area, m²; ΔV is the water volume difference, m³; Δm is the poor quality of seepage water, kg; ΔH is the head difference, m; I is the hydraulic gradient; L is the length of the specimen, m; g is the acceleration of gravity, m/s²; t is seepage time, s; ΔP is seepage pressure difference, Pa; ρ is the density of water, kg/m³.

Figure 4d shows that the overall permeability coefficient of the complete specimen is low, mostly on the order of $10^{-4} \sim 10^{-3}$ m/d. In contrast, the hydraulic conductivity of fractured specimens increased significantly, reaching the order of $10^{-3} \sim 10^{-2}$ m/d. After fracture formation, the hydraulic conductivity values of medium sandstone, fine sandstone, sandy mudstone, and coal specimens all increased. Although the intact siltstone specimen did not show obvious water permeability, its fractured specimen exhibited a certain water-conducting capacity. This also shows that the fracture structure has an important control effect on the seepage capacity of coal and rock masses.

In summary, the physical properties of boundary coal–rock pillars under long-term water accumulation are mainly as follows: The strength of coal–rock samples decreases in the saturated state, and the bearing capacity and damage resistance of coal–rock pillars decrease. After the fracture is connected, the permeability coefficient increases, and the water-proof capacity of the coal–rock column decreases.

4.2. Hydrochemical Testing Results

To investigate the hydrochemical composition of the accumulated water in the open pit and the related underground water samples, this study selected three water samples for hydrochemical testing: the water sample from the return airway of the 31112 working face (No. 1), the water sample from the accumulated water in the open pit (No. 2), and the water sample from the drainage roadway of the 31106 working face (No. 3). A Piper diagram was plotted based on the test results, as shown in Figure 4. The 31106 working face is located approximately 1500 m west and 1500 m south of the 31112 working face, at a certain distance from the influence area of the open-pit accumulated water.

In Figure 5, the left triangle diagram reflects the relative composition of the main cations in the water sample, the right triangle diagram reflects the relative composition of the main anions, and the middle diamond diagram is used to comprehensively determine the hydrochemical type of the water sample. The closer the positions of the sample points in the Piper diagram are, the more similar the main ion equivalent percentage compositions are. The TDS symbol size in the diagram reflects the relative difference of dissolved solids content in water samples.

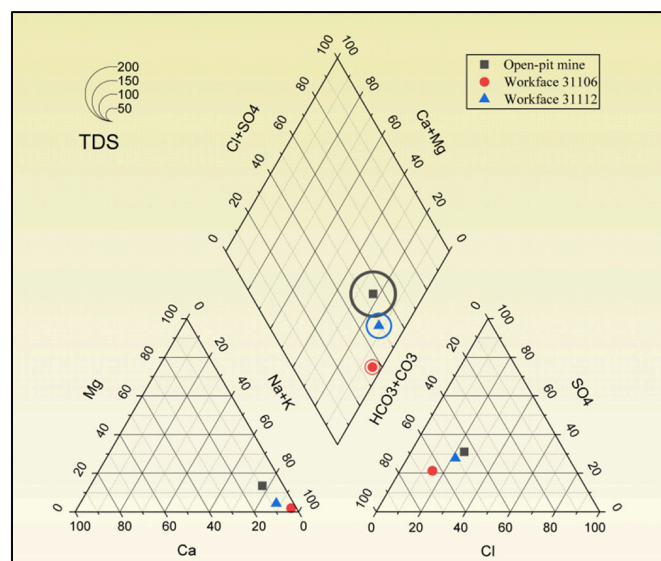


Figure 5. Piper diagram of hydrochemical test results. (The size of each circle is proportional to the TDS value.)

The projection points of the No.1 and No.2 water samples in the Piper three-line diagram are relatively close, indicating that the two have high similarity in their main ion composition. Both of them are dominated by $\text{Na}^+ + \text{K}^+$, Ca^{2+} and Mg^{2+} . The proportion is relatively low, and the anions mainly consist of $\text{HCO}_3^- + \text{CO}_3^{2-}$, while SO_4^{2-} and Cl^- occupy a certain proportion, but overall do not dominate. At the same time, the pH values of No.1 and No.2 water samples were 8.08 and 8.18, respectively, and the soluble solid contents were 970 mg/L and 908 mg/L, respectively. Both of them were weakly alkaline water, and the soluble solid content was relatively close. The above results show that the water samples of the return air along the 31112 working face and the water samples of the open pit have strong consistency in hydrochemical characteristics. In contrast, there is a certain deviation between the position of the No.3 water sample and the No.1 and No.2 water samples in the Piper diagram, indicating that the chemical composition of the water is more different. In addition, the pH of water sample No.3 is 7.30, and the soluble solid content is 1552 mg/L, which is significantly higher than that of water samples No.1 and No.2, indicating that the water sample may be affected by karst filtration, water-rock interaction, the mining fissure runoff path or local water body mixing during underground migration.

It can be seen from the comprehensive water quality test results that the water chemical types of the No.1 water sample and No.2 water sample have strong similarity in Na^+ , HCO_3^- , pH and soluble solid content, while the difference between the No.3 water sample and the former two is relatively obvious. The results show that there is a stronger hydraulic connection between the open-pit water and the adjacent underground mining space.

4.3. Calculation Results of the Water-Resisting Coal Pillar

A reasonably designed water-resisting coal pillar can effectively isolate hazardous water sources and reduce the likelihood of mine water hazards. To evaluate the rationality of coal pillar design, most coal mines calculate the width of the water-resisting coal-rock pillar using Equation (3):

$$L = 0.5KM\sqrt{3P/K_p} \quad (3)$$

where L is the width of the coal-rock pillar (m); K is the safety factor; M is the coal seam thickness (m); P is the actual water head (MPa); and K_p is the tensile strength of coal (MPa).

In this study, because the mine has long been affected by water accumulation, especially where the western water-resisting coal pillar has remained in an immersed state for a long period, its condition differs from that under normal circumstances. Therefore, the modified formula for the immersed state should be adopted [31]:

$$L = 0.5KM\sqrt{3P/R_tK_p} \quad (4)$$

where R_t is the softening coefficient of the tensile strength of the coal pillar, defined as the ratio of the uniaxial tensile strength of the coal specimen after immersion to its initial tensile strength, namely

$$R_t = \frac{\sigma_{tn}}{\sigma_t} \quad (5)$$

where σ_{tn} is the tensile strength after change, MPa; and σ_t is the tensile strength before change, MPa.

The average thickness of coal seam 2⁻² is 5 m; the thickness of coal seam 3⁻¹ is 0.85~4.67 m and the average is 3.57 m; the average thickness of the coal seam 31112 working face is 4.1 m, taken as 4 m in the calculation; the elevation of the coal seam 2⁻² floor is +1095 m; the elevation of the coal seam 3⁻¹ floor is +1055 m; and according to the maximum elevation of the Ulan Mulun River bed being +1138 m and the maximum elevation of the

open-pit water being +1110 m, for safety reasons, the water-level elevation is the highest water level in the history of the open pit, + 1110 m. In extreme cases, the maximum water level of the riverbed is +1140 m, the 2^{-2} coal p values are 0.15 and 0.55 MPa, and the 3^{-1} coal p values are 0.45 and 0.85 MPa, respectively.

As shown in Table 3, under the same coal seam conditions, the results calculated using the modified formula, which considers the reduction in tensile strength after water action, are greater than those obtained using the conventional formula. This indicates that long-term water accumulation increases the required design width of the water-resisting coal-rock pillar. For the No. 2^{-2} coal seam, when the water-level elevation increases from +1110 m to +1140 m, the corrected width increases from 10.17 m to 19.47 m. For the No. 3-1 coal seam, the corrected width increases from 13.33 m to 18.32 m. Compared with the normal calculation width, the corrected width of water accumulation increases by about 19.74%~21.94%, indicating that under the conditions of long-term water accumulation or high water level, if the conventional formula is still used, the influence of coal-rock strength reduction on the water-proof stability of coal pillars may be underestimated.

Table 3. Theoretically calculated width of the water-resisting coal-rock pillar.

Coal Seam	Water-Level Elevation/m	(R _t)	(P)/MPa	Normal Calculated Width/m	Water-Accumulation-Corrected Width/m	Increase After Water-Accumulation Correction/%
No.2 ⁻²	1110	0.67	0.15	8.34	10.17	21.94
No.2 ⁻²	1140	0.67	0.55	15.98	19.47	21.84
No.3 ⁻¹	1110	0.7	0.45	11.13	13.33	19.77
No.3 ⁻¹	1140	0.7	0.85	15.3	18.32	19.74

The calculated results are compared with the measured coal pillars. The coal pillar widths required for extreme water levels in the 2^{-2} coal seam and 3^{-1} coal seam are 19.47 m and 18.32 m, respectively. For safety considerations, 20 m is taken in the actual project, which is less than for the measured 2^{-2} coal. The minimum distance between the coal pillar and the eastern boundary coal pillar of the mine is 84.9 m, and the minimum distance between the 3^{-1} coal seam and the eastern boundary coal pillar of the mine is 74 m. This also shows that the coal pillar in the production process of the mine has to meet the needs of water insulation.

5. Discussion

5.1. Analysis of Seepage Channel Development in the Boundary Coal-Rock Pillar

The boundary coal-rock pillar is located between the open pit and the underground mining space, serving as both a water-resisting and a load-bearing structure. Under non-accumulated-water conditions, its stability is mainly controlled by the integrity, intrinsic strength, and stress state of the coal-rock pillar. However, after long-term water accumulation in the open pit, the outer boundary of the coal-rock pillar changes from a relatively open condition to a hydraulic boundary continuously subjected to water pressure. Previous studies have indicated that water accumulation after open-pit closure and groundwater-level recovery can increase pore water pressure in surrounding rock masses and alter the stress state of structural planes, thereby affecting rock mass stability [24]. This indicates that water accumulated in the open pit does not simply act as a static water body, but can continuously influence the surrounding rock mass through pore water-pressure transmission.

Considering the conditions of the study area, the water level of the accumulated water in the open pit has remained relatively high for a long period. The accumulated water covers the No. 2^{-2} coal seam, the No. 3^{-1} coal seam, and the sandstone and sandy

mudstone layers between them, providing hydrogeological conditions for lateral recharge and seepage. Meanwhile, water seepage has occurred in the auxiliary inclined shaft and the return airway of the 31112 working face, indicating that a certain hydraulic connection may exist between the accumulated water in the open pit and the underground mining space. These field observations demonstrate the existence of a hydraulic connection between the accumulated water and underground mining space; however, they cannot directly determine the specific location and geometry of seepage pathways.

Hydrochemical analysis provides further evidence for this connection. According to the Piper diagram results, the water sample from the return airway of the 31112 working face is located close to the water sample from the accumulated water in the open pit, and the two samples exhibit high similarity in terms of major ion composition, pH value, and total dissolved solids. This further supports the involvement of accumulated water in the open pit in the underground seepage process.

It is generally recognized that mine water inrush is jointly controlled by water sources and water-conducting channels. Previous studies have shown that the formation of water-conducting channels is commonly controlled by water source conditions, fracture structures, and stress–seepage coupling effects, while fracture propagation and permeability enhancement promote water migration [2]. For the study area, long-term water accumulation in the open pit provides a continuous water source and lateral hydraulic pressure for the boundary coal–rock pillar. Bedding planes, joints, primary fractures, mining-induced fractures, and weakly cemented planes inside the coal–rock pillar provide initial pathways for water infiltration. However, it should be noted that coal seams are generally considered relatively water-resisting or weakly permeable layers. Nevertheless, coal seams are not completely dense media. Since the coal seams in the study area are within the inundated range of the accumulated water, long-term water accumulation and lateral hydraulic pressure may induce weak water-conducting zones within the coal seam, which can participate in water-pressure transmission and potential seepage channel development inside the boundary coal–rock pillar.

The permeability test results in this study further indicate that intact specimens generally exhibit low hydraulic conductivity, whereas fractured specimens show significantly increased hydraulic conductivity, demonstrating that fracture development and connectivity strongly control the water-conducting capacity of coal–rock masses. Therefore, under long-term lateral hydraulic pressure, water is more likely to preferentially migrate along well-connected fractures, bedding planes, coal cleats, and weakly cemented zones rather than diffuse uniformly within the coal–rock pillar. As local pore–fracture systems become further connected, originally dispersed weak structural planes may gradually develop into seepage channels with a certain water-conducting capacity.

Based on field seepage phenomena, hydrochemical similarity, and permeability test results, the influence process of accumulated water in the open pit on the underground mining space is generalized as a continuous “water source–seepage channel–working face” model (Figure 6). In this model, accumulated water in the open pit serves as a continuous water source, while the pore–fracture network, bedding planes, and mining-induced fractures inside the boundary coal–rock pillar constitute potential seepage channels. Water-pressure transmission and pore–fracture connection control the possibility of water migration toward the working face. It should be emphasized that the seepage channels proposed in this study do not refer to the instantaneous connection of a single fracture, but rather represent a progressive process in which pores, fractures, and bedding planes gradually become interconnected and their water-conducting capacity increases under the combined effects of long-term water accumulation, lateral hydraulic pressure, and weak structural planes within the coal–rock mass.

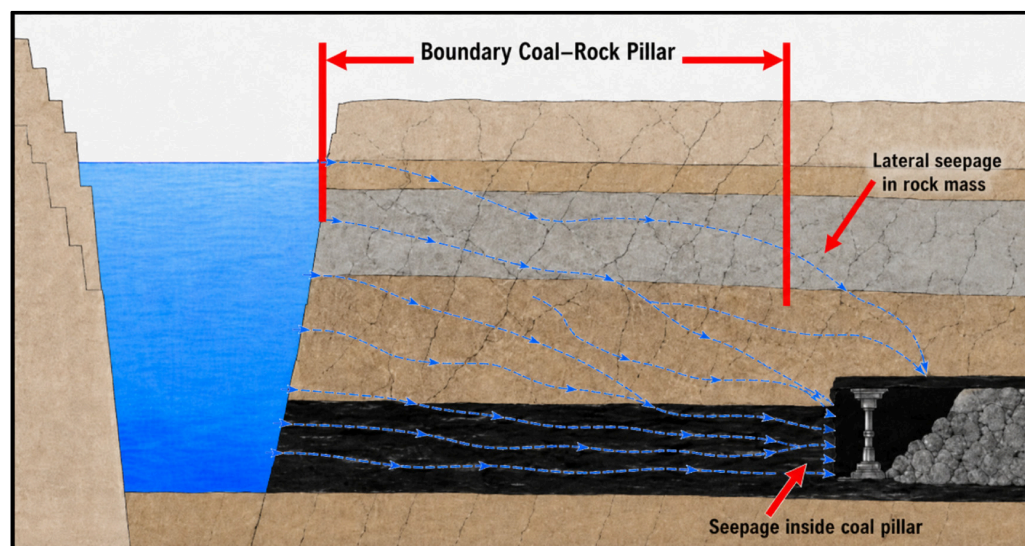


Figure 6. Schematic diagram of the seepage process of water accumulation in the open pit. (The blue arrows indicate the seepage direction of groundwater.)

5.2. Influence Mechanism of Water Accumulation in the Open Pit on the Physical Properties of Coal and Rock

The preceding test results indicate that the average strength of coal and rock specimens in the natural state is higher than that in the saturated state, while their permeability in the natural state is also significantly lower. Previous studies have shown that the more developed the pore and fracture structures in coal, the easier it is for water to migrate into the coal mass along pores and fractures, weakening interparticle bonding and deteriorating its mechanical properties. In addition, immersion duration and hydrochemical characteristics are important factors affecting coal pillar stability [31], which is consistent with the experimental results obtained in this study.

After entering the coal–rock pillar, water gradually reduces interparticle cementation and frictional resistance along fracture surfaces. For sandstone specimens, water mainly weakens particle cementation, reduces the frictional strength of microfracture surfaces, and promotes fracture propagation (Figure 7). For specimens with higher clay mineral content, water exposure can induce swelling, softening, and local argillization of clay minerals, resulting in the weakening of bedding planes and weakly cemented surfaces. These effects ultimately lead to reductions in uniaxial compressive strength, tensile strength, and shear strength.

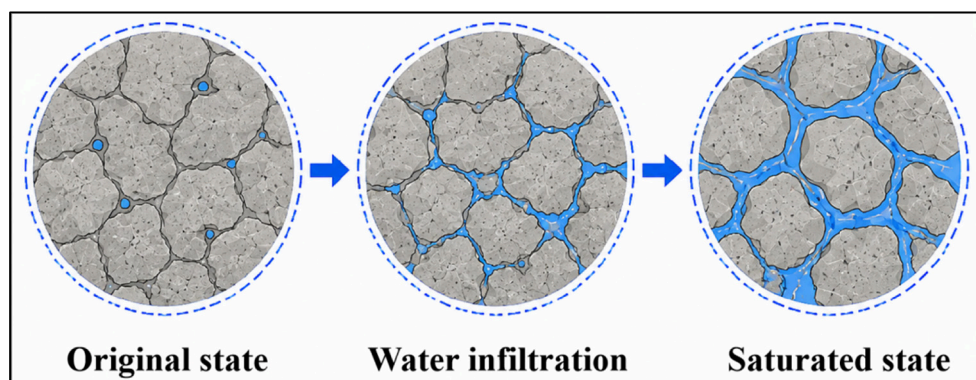


Figure 7. Schematic diagram of pore–fracture structure evolution in the coal–rock pillar.

The permeability test results show that intact specimens generally exhibit low hydraulic conductivity, indicating that the water-conducting capacity of the coal–rock matrix is limited before the formation of obvious through-going fractures. In contrast, the hydraulic conductivity of fractured specimens increases significantly, demonstrating that fracture development and connectivity can substantially reduce seepage resistance and enhance the water-conducting capacity of the coal–rock pillar. Previous studies have shown that an increase in water content in coal samples promotes fracture propagation and porosity growth, thereby reducing seepage resistance and increasing average flow velocity. In comparison, under conditions of lower water content and larger coal pillar width, coal samples exhibit higher strength, smaller axial deformation, and lower permeability and porosity. As internal damage within the coal pillar intensifies, both porosity and water flow velocity increase simultaneously [3]. These findings further support the previous discussion that, under long-term water accumulation, the coal seam itself may also become a pathway for water migration.

Overall, water accumulated in the open pit first migrates into the coal–rock pillar along seepage pathways, altering its water-bearing state. Subsequently, water weakens particle cementation and the shear resistance of structural planes, resulting in reductions in the mechanical strength and overall bearing capacity of the coal–rock pillar. Meanwhile, these changes are accompanied by enhanced permeability of the coal–rock pillar.

5.3. Mechanism of the Influence of Water Accumulation in the Open Pit on Coal–Rock Pillar Stability

The boundary coal–rock pillar is an engineering structure composed of coal seams, partings, roof and floor strata, and internal structural planes. Therefore, its stability cannot be evaluated solely based on the strength of individual coal and rock specimens. For the research object in this study, water accumulation in the open pit imposes lateral hydraulic pressure, pore water pressure, and long-term water–rock interaction on the boundary coal–rock pillar in addition to the original in situ stress and mining-induced stress, resulting in a clear multi-factor coupled stability evolution process.

The influence of water accumulation in the open pit on the stability of the boundary coal–rock pillar can be regarded as a progressive evolution process from the outside toward the interior [32]. First, long-term water accumulation in the open pit changes the external hydraulic boundary conditions of the boundary coal–rock pillar, causing its outer side to continuously experience lateral hydraulic pressure. Subsequently, water infiltrates into the interior of the coal–rock pillar along pre-existing pathways and gradually forms preferential seepage channels in local areas. Under the combined effects of water pressure, water–rock interaction, and stress disturbance, the cementation structure of the coal–rock mass and the stability of weak structural planes are weakened. Fractures further propagate, permeability increases, and water pressure can continue to transmit toward the interior of the coal–rock pillar.

With the long-term influence of water accumulation in the open pit, the coal–rock mass near the water side is more susceptible to water-induced deterioration and fracture development, gradually transforming into a water-pressure damage zone or plastic failure zone. In contrast, the relatively intact, low-permeability region inside the coal–rock pillar with higher bearing capacity constitutes the main effective water-resisting and bearing zone. The theoretical calculation results for the water-resisting coal–rock pillar indicate that water immersion reduces the tensile strength of coal specimens and increases the required pillar width compared with conventional calculations, demonstrating that long-term water accumulation imposes higher requirements on the effective width and structural integrity of the boundary coal–rock pillar.

Consequently, a continuous process of “channel formation–sustained seepage–strength degradation–enhanced pore–fracture connectivity–permeability enhancement–further stability reduction” is established (Figure 8). Through this process, the boundary coal–rock pillar gradually evolves from local water influence on the outer side to continuous internal structural weakening, ultimately resulting in the simultaneous reduction in its water-resisting capacity and bearing capacity.

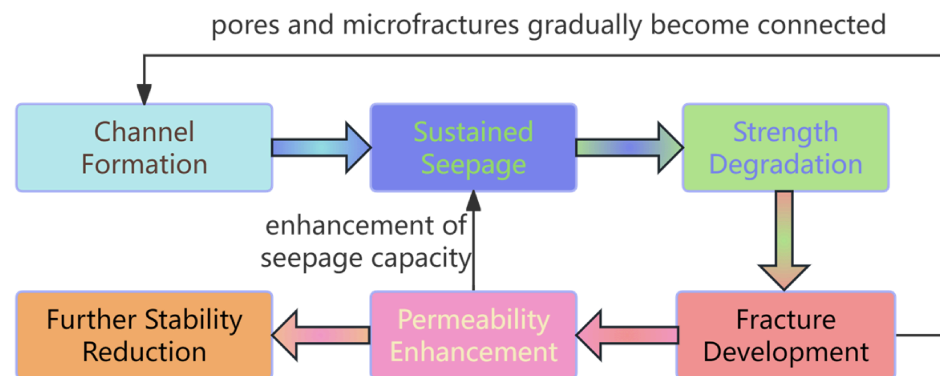


Figure 8. Schematic diagram of the seepage–damage evolution mechanism of the boundary coal–rock pillar under the influence of water accumulation in the open pit.

5.4. Limitations and Future Perspectives

This study mainly analyzed the influence of open-pit water accumulation on the stability of boundary coal–rock pillars based on field sampling, laboratory tests, water quality analysis, permeability tests, and theoretical calculation. However, due to the limitations of the current research conditions, numerical simulations and similar-material model tests were not conducted to further verify the stress field, seepage field, and damage evolution process inside the coal–rock pillar. Therefore, the understanding of the stability evolution mechanism of boundary coal–rock pillars under long-term water accumulation still needs to be supplemented and verified by additional methods.

Future research will further combine numerical simulation and similar-material modeling to investigate the stress–seepage coupling characteristics, seepage channel formation process, and stability evolution of boundary coal–rock pillars under water accumulation. At present, preliminary similar-material model tests have been initiated. The simulation results will be compared with the experimental data in future work to improve the reliability and applicability of the conclusions.

6. Conclusions

1. Long-term water accumulation in the open pit changes the external hydraulic boundary of the boundary coal–rock pillar, causing it to continuously experience lateral hydraulic pressure. Water can migrate into the coal–rock pillar along bedding planes, primary fractures, mining-induced fractures, and coal seam fractures, promoting the propagation and connection of existing pores and fractures, and gradually forming preferential seepage pathways in local areas. Consequently, hydraulic connections between the accumulated water in the open pit and the underground mining space may develop through seepage channels within the coal–rock pillar.
2. Long-term water accumulation alters the physical properties and internal structure of the coal–rock pillar, resulting in strength degradation, reduced overall stability, and enhanced permeability. Specifically, the deterioration rates of the uniaxial compressive strength of rock specimens range from -8.75% to -50.64% , while those of No.2⁻² and No.3⁻¹ coal specimens are -17.72% and -25.01% , respectively. The tensile

deterioration rates of coal and rock specimens range from -24.59% to -59.11% , and the shear strength decreases by -7.53% – -50.79% . The hydraulic conductivity of intact specimens is generally low, mainly ranging from 10^{-4} to 10^{-3} m/d, whereas that of fractured specimens increases significantly, reaching 10^{-3} – 10^{-2} m/d.

3. Under the influence of water accumulation in the open pit, the stability evolution of the boundary coal–rock pillar is a coupled process in which seepage channel development and physical property changes mutually promote each other. Long-term water accumulation induces a continuous process of “channel formation–sustained seepage–strength degradation–enhanced pore–fracture connectivity–permeability enhancement–further stability reduction.” This process gradually expands the water-affected zone and plastic failure zone, continuously reduces the effective water-resisting and bearing zone, and ultimately decreases the water-resisting capacity and stability of the boundary coal–rock pillar. Considering the influence of long-term water accumulation, the required widths of the No.2⁻² and No.3⁻¹ coal seams increase by 21.84–21.94% and 19.74–19.77%, respectively.

Author Contributions: Conceptualization, J.H. and C.L.; methodology, J.X.; validation, J.H. and C.L.; formal analysis, J.H.; investigation, H.Z.; resources, Y.Z.; data curation, J.H. and H.Z.; writing—original draft preparation, J.H.; writing—review and editing, C.L.; visualization, J.H.; supervision, J.X.; project administration, Y.Z.; funding acquisition, C.L. and J.X. All authors have read and agreed to the published version of the manuscript.

Funding: The authors declare that this study received funding from the Major Science and Technology Projects of Xinjiang Uygur Autonomous Region (No. 2024A01003), the National Natural Science Foundation of China (No. 42502232, 52274243), and the Fundamental Research Funds for the Central Universities (No. 2024QN11025). The funders had the following involvement with the study: Conceptualization, validation, writing—review and editing.

Data Availability Statement: The original data supporting the findings of this study are included in the article and its Appendix A. Further inquiries can be directed to the corresponding author.

Acknowledgments: We would like to express our sincere gratitude for the financial support provided by these funding projects.

Conflicts of Interest: Author Yongqiang Zhang was employed by the company Inner Mongolia Shendong Tianlong Group Co. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

Appendix A

The original experimental data used in this study are provided in Appendix A, including the mechanical test results, permeability test results, and hydrochemical test data. These data were used for calculating the average values, deterioration rates, and comparative results presented in the main text. Damaged samples or samples that did not meet the effective testing requirements were excluded from the statistical analysis, as described in the corresponding sections of the manuscript.

Table A1. Raw data table of the uniaxial compressive strength test for rock samples.

Failure Load (N)							Shear Strength (MPa)						
Lithology	No.	No. 1	No. 2	No. 3	Average of Samples 1–3	Saturated Sample	Lithology	No.	No. 1	No. 2	No. 3	Average of Samples 1–3	Saturated Sample
Fine sandstone	1 m	90,819.35			90,819.35			1 m	46.28			46.28	
	2 m	86,194.47			86,194.47	Failed along fissure		2 m	43.92			43.92	
	3 m	76,051.34	75,597.23		75,824.29	62,793.68	Fine sandstone	3 m	38.75	38.52		38.64	32.00
	4 m	209,116.5			209,116.50	14,4032.6		4 m	106.56			106.56	73.39
	5 m	185,720.6	96,174.73		140,947.67			5 m	94.63	49.01		71.82	
	6 m	149,575.5			149,575.50	142,423.5		6 m	76.22			76.22	72.57
Medium sandstone	7 m	115,799.6	87,981.24	154,570.6	119,450.48	56,989.14		7 m	59.01	44.83	78.76	60.87	29.04
	8 m	90,918.06	83,810.46	83,124.38	85,950.97	55,024.68		8 m	46.33	42.71	42.36	43.80	28.04
	9 m	66,880.55	86,357.35		76,618.95	58,376.11		9 m	34.08	44.00		39.04	29.75
	10 m	102,003.9	92,981.24	81,426.45	92,137.20	52,097.73		10 m	51.98	47.38	41.49	46.95	26.55
	11 m	93,553.8			93,553.80	Failed along fissure		11 m	47.67			47.67	
	12 m	85,908.2	105,138.2		96,872.33	30,162.88		12 m	43.77	53.57	50.74	49.36	15.37
	13 m	70,528.13	104,758.1		87,643.12	49,960.51		13 m	35.94	53.38		44.66	25.46
	14 m	90,592.3	81,451.13		86,021.72	Disintegrated after immersion	Medium sandstone	14 m	46.16	41.50		43.83	
	15 m	69,002.96	55,014.81		62,008.89	47,685.09		15 m	35.16	28.03		31.60	24.30
	16 m	86,243.83	75,513.33		80,878.58	Disintegrated after immersion		16 m	43.95	38.48		41.21	
	17 m	78,529.13	61,322.8		69,925.97	Disintegrated after immersion		17 m	40.01	31.25		35.63	
	18 m	59,871.67	57,537.02	71,041.46	62,816.72	51,046.4		18 m	30.51	29.32	36.20	32.01	26.01
	19 m	113,297.1	120,987.2		117,142.15	35,182.63		19 m	57.73	61.65		59.69	17.93
	20 m	66,406.71			66,406.71			20 m	33.84			33.84	
	21 m	75,000.01			75,000.01	39,817.38		21 m	38.22			38.22	20.29
	22 m	63,736.43			63,736.43			22 m	32.48			32.48	
	23 m	75,296.15	76,752.22		76,024.19	47,778.88		23 m	38.37	39.11		38.74	24.35
Fine sandstone	24 m	89,343.53	83,617.97		86,480.75	Failed along fissure	Fine sandstone	24 m	45.53	42.61		44.07	
	25 m	98,440.27			98,440.27			25 m	50.16			50.16	
Siltstone	26 m	97,013.82	106,100.7		10,1557.26	40,276.41	Siltstone	26 m	49.43	54.06		51.75	20.52
	27 m	100,834.2	85,952.62		93,393.41	52,364.27		27 m	51.38	43.80		47.59	26.68
	28 m	82,783.81	115,829.2		99,306.51	58,242.84		28 m	42.18	59.02		50.60	29.68
Sandy mudstone	29 m	107,393.9			107,393.90	31,737.41	Sandy mudstone	29 m	54.72			54.72	16.17
	30 m	79,713.72	70,256.66		74,985.19	46,910.17		30 m	40.62	35.80		38.21	23.90
	31 m	68,933.86	113,756.2		91,345.03	58,613.03		31 m	35.13	57.96		46.55	29.87
	32 m	172,073.1	90,829.22		131,451.16	82,117.48		32 m	87.68	46.28		66.98	41.84
Siltstone	33 m	76,100.69	75,755.18		75,927.94	38,524.19	Siltstone	33 m	38.78	38.60		38.69	19.63
	34 m	86,510.37	92,833.17		89,671.77	Disintegrated after immersion		34 m	44.08	47.30		45.69	
	35 m	104,432.4	92,300.1		98,366.25	56,539.98		35 m	53.21	47.03		50.12	
	36 m	90,197.43	96,910.16		93,553.80	Failed along fissure		36 m	45.96	49.38		47.67	28.81
	37 m	95,029.62	101,954.6		98,492.11			37 m	48.42	51.95		50.19	

Table A1. Cont.

Failure Load (N)							Shear Strength (MPa)									
Lithology	No.	No. 1	No. 2	No. 3	Average of Samples 1-3	Saturated Sample	Lithology	No.	No. 1	No. 2	No. 3	Average of Samples 1-3	Saturated Sample			
Sandy mudstone	38 m	88,188.55	102,226.1		88,188.55	38,168.8	Sandy mudstone	38 m	44.94	52.09		44.94	19.45			
	39 m	97,082.92			99,654.51	35,760.12		39 m	49.47			50.78	18.22			
	40 m	67,418.56			67,418.56			40 m	34.35			34.35				
	41 m							41 m								
	42 m							42 m								
	43 m							43 m								
	44 m								44 m							

Table A2. Raw data table of the uniaxial tensile strength test for rock samples.

Failure Load (N)						Tensile Strength (MPa)								
Lithology	No.	No. 1	No. 2	Average of Samples 1–2	Saturated Sample	Lithology	No.	No. 1	No. 2	Average of Samples 1–2	Saturated Sample			
Fine sandstone	1 m	3849.36	3089.83	3849.36	3395.85	Fine sandstone	1 m	1.96	1.57	1.96	1.73			
	2 m	4452.12		3770.98	3374.24		2 m	2.27		1.92	1.72			
	3 m	2403.75		2403.75	6490.62		3 m	1.22		1.22	3.31			
	4 m	11431.39		11431.39			4 m	5.82		5.82				
	5 m	5157.95		5157.95			5098.07	5 m		2.63		2.63	2.60	
	6 m	6643.63		6643.63			6 m	3.39		3.39				
Medium sandstone	7 m	4091.81	3568.16	3829.99	3382.03	Medium sandstone	7 m	2.08	1.82	1.95	1.72			
	8 m	3953.61	6110.56	5032.09	2161.89		8 m	2.01	3.11	2.56	1.10			
	9 m	3953.61	4748.27	4350.94	1722.61		9 m	2.01	2.42	2.22	0.88			
	10 m	1924.98	2961.5	2443.24			10 m	0.98	1.51	1.24				
	11 m	3958.54	2769.01	3958.54	1732.48		11 m	2.02	1.41	2.02	0.88			
	12 m	2821.65		2795.33	1834.72		12 m	1.44		1.42	0.93			
	13 m	4753.21		4217.67	2285.29		13 m	2.42		1.88	2.15	1.16		
	14 m	3428.37		2408.69	2918.53		1189.54	14 m		1.75	1.23	1.49	0.61	
	15 m	3297.18		4822.31	4059.75		1732.48	15 m		1.68	2.46	2.07	0.88	
	16 m	2877.59	3810.46	3344.03	1110.56		16 m	1.47	1.94	1.70	0.57			
	17 m	4076.99	1214.21	2645.60	Failed along fissure		17 m	2.08	0.62	1.35	0.66			
	18 m	2562.18	2073.05	2317.62	1303.06		18 m	1.31	1.06	1.18				
	19 m	6416.58	2749.26	4582.92	3469.89		19 m	3.27	1.40	2.34		1.77		
	20 m	3484.69	2566.63	3484.69	1386.96		20 m	1.78	1.31	1.78		0.71		
	21 m	3089.83		2828.23	1006.91		21 m	1.57		1.44		0.51		
	22 m	1583.26		2954.18	2268.72		1032.58	22 m		0.81		1.51	1.16	0.53
	23 m	1391.91		1028.34	1210.13		952.82	23 m		0.71		0.52	0.62	0.49
	Fine sandstone	24 m	3395.85	4294.18	3845.02		853.92	Fine sandstone	24 m	1.73		2.19	1.96	0.44
		25 m	2275.42	2240.87	2258.15				25 m	1.16	1.14	1.15		
Siltstone	26 m	3430.41	3089.84	3260.13	Failed along fissure	Siltstone	26 m	1.75	1.57	1.66	0.70			
	27 m	3158.94	2615.99	2887.47			27 m	1.61	1.33	1.47				
	28 m	4777.88	4521.22	4649.55	1368.31		28 m	2.43	2.30	2.37				

Table A2. Cont.

Failure Load (N)						Tensile Strength (MPa)					
Lithology	No.	No. 1	No. 2	Average of Samples 1–2	Saturated Sample	Lithology	No.	No. 1	No. 2	Average of Samples 1–2	Saturated Sample
Sandy mudstone	29 m	3079.96		3079.96		Sandy mudstone	29 m	1.57		1.57	
	30 m	3469.89	1658.44	2564.17	1485.69		30 m	1.77	0.85	1.31	0.76
	31 m	3677.19	2324.78	3000.99	2361.52		31 m	1.87	1.18	1.53	1.20
	32 m	11,663.38	3524.19	7593.79	2546.89		32 m	5.94	1.80	3.87	1.30
Siltstone	33 m	8504.44		8504.44	1110.56	Siltstone	33 m	4.33		4.33	0.57
	34 m	2230.99	2102.67	2166.83	1229.02		34 m	1.14	1.07	1.10	0.63
	35 m	2300.09	4205.33	3252.71	2571.57		35 m	1.17	2.14	1.66	1.31
	36 m	2936.82	3124.38	3030.60	1604.15		36 m	1.50	1.59	1.54	0.82
	37 m	1753.61		1753.61			37 m	0.89		0.89	
Sandy mudstone	38 m	3647.58		3647.58	2527.15	Sandy mudstone	38 m	1.86		1.86	1.29
	39 m						39 m				
	40 m	2142.15		2142.15	1372.16		40 m	1.09		1.09	0.70
	41 m						41 m				
	42 m	2877.59		2877.59			42 m	1.47		1.47	
	43 m						43 m				
	44 m	4358.34		4358.34			44 m	2.22		2.22	

Table A3. Raw data table of the uniaxial shear strength test for rock samples.

Failure Load (N)						40°		50°		60°		Saturated Sample		
Lithology	No.	40°	50°	60°	Saturated Sample	Normal Stress	Shear Stress	Normal Stress	Shear Stress	Normal Stress	Shear Stress	Normal Stress	Shear Stress	Saturated Sample Angle
Fine sandstone	1 m		23,810.46					7.82	9.27					40
	2 m		22,877.59		20,074.04			7.52	8.91			6.60	7.82	50
	3 m	38,070.09	30,167.82		18,746.3	14.84	12.50	9.91	11.75			4.75	8.29	60
	4 m	98,849.95	44,457.06	35,133.27	70,360.31	38.52	32.45	14.61	17.31	8.91	15.53	27.42	23.10	40
	5 m	69,378.09			56,929.91	27.04	22.77					22.19	18.69	40
	6 m	52,522.21			48,020.73	20.47	17.24					12.18	21.23	60
Medium sandstone	7 m		69,037.52		44,856.86			22.68	26.89			17.48	14.72	40
	8 m	38,889.44		15,478.78	43,598.22	15.16	12.77			3.92	6.84	22.22	16.98	50
	9 m		23,321.82	25,518.26	21,115.5			7.66	9.08	6.47	11.28	5.35	9.33	60
	10 m	34,886.48		13,307.01	26,382.03	13.60	11.45			3.37	5.88	10.28	8.66	40
	11 m		29,091.81		17,117.47			9.56	11.33			5.62	6.67	50
	12 m	44,234.95		20,607.11	12,991.12	17.24	14.52			5.22	9.11	3.29	5.74	60
	13 m		25,814.41		21,026.65			8.48	10.05			6.91	8.19	50
	14 m	65,444.23	37,018.76		30,700.89	25.51	21.48	12.16	14.42			11.97	10.08	40
	15 m		35,824.29		Failed along fissure			11.77	13.95					
	16 m	47,798.62			13,005.92	12867.72	18.63	15.69				5.75	3.26	60
	17 m			15,320.83	20,207.3					3.88	6.77	7.88	6.63	40
	18 m	28,257.65	31,574.53		12,680.16	11.01	9.28	10.37	12.30			4.17	4.94	50
	19 m			22,191.51	14,526.16					5.63	9.81	3.68	6.42	60
	20 m		29,595.26		20,523.2			9.72	11.53			8.00	6.74	40
	21 m	23,445.21	28,366.24			9.14	7.70	9.32	11.05					
	22 m		17,887.46		16,811.45			5.88	6.97			5.52	6.55	50
	23 m			14,249.75	12,946.69					3.61	6.30	3.28	5.72	60

Table A3. Cont.

Lithology	No.	Failure Load (N)		40°		50°		60°		Saturated Sample		Saturated Sample Angle
		40°	50°	60°	Saturated Sample	Normal Stress	Shear Stress	Normal Stress	Shear Stress	Normal Stress	Shear Stress	
Fine sandstone	24 m	37,541.95		10,009.87	23,035.54	14.63	12.32			2.54	4.42	40
	25 m		23,519.25		23,247.78			7.73	9.16		7.64	50
Siltstone	26 m	15,513.33		18,874.63	14,432.38	6.05	5.09			4.79	8.34	60
	27 m	46,826.26			22,201.38	18.25	15.37				7.29	50
	28 m		22,280.36	21,456.07				7.32	8.68	5.44	9.48	
Sandy mudstone	29 m	28,958.54			16,233.96	11.29	9.51				5.33	50
	30 m	31,016.78	41,342.55	14,106.61		12.09	10.18	13.58	16.10	3.58	6.24	
	31 m		30,592.3	24,422.51	17,171.77			10.05	11.91	6.19	10.79	60
	32 m		91,663.38		42,413.62			30.12	35.70		16.53	40
Siltstone	33 m	47,453.11	44,955.58		64,353.41	18.49	15.58	14.77	17.51		21.14	50
	34 m	55,375.13		22,917.08		21.58	18.18			5.81	10.13	
	35 m		38,998.03		7156.96			12.81	15.19		1.81	60
	36 m			14,807.5						3.75	6.54	
	37 m		40,824.29		30,676.21			13.41	15.90		11.96	40
Sandy mudstone	38 m	67,235.93			Failed along fissure	26.20	22.07					
	39 m		34,664.36					11.39	13.50			
	40 m				27,003.95						10.52	40
	41 m											
	42 m			25,034.55						6.35	11.07	

Table A4. Raw data table of the uniaxial compressive strength test for coal samples.

No. 2 ^{−2} Coal	1	2	3	4	5 (saturated)	6 (saturated)
Failure load (N)	48,571.6	47,812.6	52,103.8	42,851.7	40,287.9	38,423.7
Uniaxial compressive strength (MPa)	24.75	24.36	26.55	21.84	20.53	19.58
No. 3 ^{−1} Coal	1	2	3	4	5 (saturated)	6 (saturated)
Failure load (N)	67,620.93	45,784.8	59,669.3	41,648.57	39,528.4	42,861.72
Uniaxial compressive strength (MPa)	34.46	23.33	30.4	23.77	20.14	21.84

Table A5. Raw data table of the uniaxial tensile strength test for coal samples.

No. 2 ^{−2} Coal	1	2	3	4 (saturated)	5 (saturated)	6 (saturated)
Failure load (N)	2147.08	1769.17	2061.82	1456.07	1382.03	1204.34
Tensile strength (MPa)	1.09	0.9	1.05	0.74	0.7	0.61
No. 3 ^{−1} Coal	1	2	3	4 (saturated)	5 (saturated)	6 (saturated)
Failure load (N)	2257.65	2164.07	2010.86	1657.21	1522.64	1317.83
Tensile strength (MPa)	1.15	1.1	1.02	0.84	0.78	0.67

Table A6. Raw data table of the uniaxial shear strength test for coal samples.

Coal Seam Horizon	Sample No.	Fixture Angle	Failure Load	Normal Stress	Shear Stress	Cohesion	Internal Friction Angle
2 ^{−2} Coal	1	50°	25,487.9	8.37	9.93	4.86	31.75
	2		26,741.8	8.79	10.42		
	3		15,627.8	3.96	6.91		
	4	60°	18,472.6	4.68	8.16		
	5 (saturated)		22,187.2	8.65	7.28		
	6 (saturated)		13,127.5	5.12	4.31		
3 ^{−1} Coal	1	40°	44,629.81	17.39	14.65	6.62	23.85
	2		41,475.81	16.16	13.62		
	3		27,709.77	9.1	10.79		
	4	50°	29,624.88	9.73	11.54		
	5		18,741.36	4.75	8.28		
	6		21,475.81	5.44	9.49		
	7 (saturated)	40°	38,859.82	15.14	12.76		
	8 (saturated)	50°	27,694.96	9.1	10.79		
	9 (saturated)	60°	18,242.84	4.63	8.06		

References

- Ju, F.; Wang, D.; Wang, Z.W. Coal Pillar Stability Investigation for High-Intensity Mining in the Water-Rich Coal Seam: A Case Study. *Min. Metall. Explor.* **2024**, *41*, 743–768. [[CrossRef](#)]
- Ma, D.; Duan, H.Y.; Zhang, J.X.; Bai, H. A State-of-the-Art Review on Rock Seepage Mechanism of Water Inrush Disaster in Coal Mines. *Int. J. Coal Sci. Technol.* **2022**, *9*, 50. [[CrossRef](#)]
- Liu, Q.; Xue, Y.; Ma, D.; Li, Q. Failure Characteristics of the Water-Resisting Coal Pillar under Stress-Seepage Coupling and Determination of Reasonable Coal Pillar Width. *Water* **2023**, *15*, 1002. [[CrossRef](#)]
- Viswanathan, H.S.; Ajo-Franklin, J.; Birkholzer, J.T.; Carey, J.W.; Guglielmi, Y.; Hyman, J.D.; Karra, S.; Pyrak-Nolte, L.J.; Rajaram, H.; Srinivasan, G.; et al. From Fluid Flow to Coupled Processes in Fractured Rock: Recent Advances and New Frontiers. *Rev. Geophys.* **2022**, *60*, e2021RG000744. [[CrossRef](#)]
- Gao, J.Y.; Peng, S.Y.; Chen, G.Q.; Mitani, Y.; Fan, H. Coupled Hydro-Mechanical Analysis for Water Inrush of Fractured Rock Masses Using the Discontinuous Deformation Analysis. *Comput. Geotech.* **2023**, *156*, 105247. [[CrossRef](#)]
- Moser, B.; Cook, P.G.; Miller, A.D.; Dogramaci, S.; Wallis, I. The Hydraulic Evolution of Groundwater-Fed Pit Lakes after Mine Closure. *Groundwater* **2024**, *62*, 889–903. [[CrossRef](#)]

7. Fan, J.; Li, Z.; Feng, G.; Zhang, H.; Qi, C.; Zhang, J. Failure Analysis of Coal Pillars and Overburden from Underground Water Reservoir under the Mining-Water Invasion Coupling Effect. *Eng. Fail. Anal.* **2023**, *151*, 107406. [\[CrossRef\]](#)
8. Shi, Z.X.; Zhu, G.G.; Zi, Z.K. Research on Water Immersion Damage Characteristics and Equivalent Width of Coal Pillar. *Sci. Rep.* **2024**, *14*, 31456. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Zhang, J.; Gao, S.; Liu, H.; Yang, T.; Wu, J.; He, Y.; Jia, Z. Study on Roadway Roof Deformation and Coal Pillar Energy Accumulation Instability. *Sci. Rep.* **2024**, *14*, 27603. [\[CrossRef\]](#) [\[PubMed\]](#)
10. Chi, G.M.; Zhang, L.H. Emergency Treatment and Follow-Up Control Scheme for the Extra-Large Water Inrush Accident in Huhe Wusu Coal Mine. *Coal Eng.* **2015**, *47*, 71–73. (In Chinese)
11. Dong, F.Y.; Yin, H.Y.; Feng, Q.F.; Li, S.; Zhou, W.; Cheng, W.; Qiu, M.; Shi, Y.; Jia, C. A New Insight of Water Inrush Mode and Coal (Rock) Pillars Setting in Near-Fault Mining under High Confined Water. *J. Appl. Geophys.* **2023**, *216*, 105136. [\[CrossRef\]](#)
12. Li, X.; Yi, S.; Chen, Z.; Guo, Q.; Cai, X.; Guo, X.; Yi, H. Insight into the Creep Damage Evolution in Water-Immersed Coal Pillars: Experiment and Numerical Model Investigation. *Energies* **2025**, *18*, 3340. [\[CrossRef\]](#)
13. Shangguan, J.H.; Guo, H.T.; Cao, S.G.; Sun, J. Study on Damage Rupture and Crack Evolution Law of Coal Samples under the Influence of Water Immersion Pressure. *Water* **2025**, *17*, 263. [\[CrossRef\]](#)
14. Yao, Q.; Tang, C.; Xia, Z.; Liu, X.; Zhu, L.; Chong, Z.; Hui, X. Mechanisms of Failure in Coal Samples from Underground Water Reservoir. *Eng. Geol.* **2020**, *267*, 105494. [\[CrossRef\]](#)
15. Xu, Z.M.; Xiong, S.J.; Yuan, H.Q.; Sun, Y.; Han, Y.; Chen, T.; Lu, W. Simulation Experiment on Structural Evolution and Damage Deterioration Mechanism of Water-Immersed Boundary Coal Pillars in Abandoned Goaf. *J. China Coal Soc.* **2025**, *50*, 1100–1114. (In Chinese)
16. Liu, F.Y.; Yang, K.; Yang, T.H.; Gao, Y.; Li, J.; Liu, Q.; Fu, Q. Pumped Storage Hydropower in an Abandoned Open-Pit Coal Mine: Slope Stability Analysis under Different Water Levels. *Front. Earth Sci.* **2022**, *10*, 941119. [\[CrossRef\]](#)
17. Chen, W.; Liu, J.; Peng, W.Q.; Zhao, Y.; Luo, S.; Wan, W.; Wu, Q.; Wang, Y.; Li, S.; Tang, X.; et al. Aging Deterioration of Mechanical Properties on Coal-Rock Combinations Considering Hydro-Chemical Corrosion. *Energy* **2023**, *282*, 128770. [\[CrossRef\]](#)
18. Ding, S.; Tang, S.B. Mechanical Behavior Evolution and Failure Characteristics of Saturated and Dry Rocks under Different Water Pressure Environments. *Int. J. Rock Mech. Min. Sci.* **2024**, *178*, 105777. [\[CrossRef\]](#)
19. Li, X.; Hu, Y.; Zhang, Y.; Kong, F.; Wang, W. Effect of Immersion Height on Coal Mechanical Properties and the Mechanism of Damage Failure. *Sci. Rep.* **2025**, *15*, 18153. [\[CrossRef\]](#) [\[PubMed\]](#)
20. Wang, B.; Zhou, D.; Zhang, J.; Liang, B. Study on the Strength Deterioration Characteristic and Damage Model of Coal Pillar Dams with Repeated Water Immersion in Underground Reservoirs. *Sci. Rep.* **2024**, *14*, 6338. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Zikun, P.; Rui, L.; Yan, W.; Jiawen, X.; Jiayi, L.; Yifu, Z.; Bin, P. Experimental Investigation into the Impact of Cyclic High-Low Pressure Water Immersion on the Pore Structure and Mechanical Properties of Coal. *Sci. Rep.* **2025**, *15*, 1288. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Zhao, Y.; Yang, T.; Zhang, P.; Xu, H.; Wang, S. Inversion of Seepage Channels Based on Mining-Induced Microseismic Data. *Int. J. Rock Mech. Min. Sci.* **2020**, *126*, 104180. [\[CrossRef\]](#)
23. Kemanga, B.; McIntyre, N.; Bulovic, N. Hydrological Classification of Mine Pit Lakes Using Modelling Experiments. *J. Environ. Manag.* **2024**, *370*, 123057. [\[CrossRef\]](#)
24. Gao, Y.; Li, J.; Yang, T.; Meng, L.; Deng, W.; Zhang, P. Formation of Pit Lake and Slope Stability Following Mine Closure: A Case Study of Fushun West Open-Pit Mine. *Geomat. Nat. Hazards Risk* **2024**, *15*, 2340612. [\[CrossRef\]](#)
25. Ye, Z.; Ghassemi, A. Injection-Induced Propagation and Coalescence of Preexisting Fractures in Granite under Triaxial Stress. *J. Geophys. Res. Solid Earth* **2019**, *124*, 7806–7821. [\[CrossRef\]](#)
26. Chengdu Engineering Corporation Limited of Power China; General Institute of Hydropower and Water Resources Planning and Design; China Electricity Council. *Standard for Test Methods of Engineering Rock Mass*; Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China; General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China: Beijing, China, 2013; p. 132. (In Chinese)
27. Changjiang River Scientific Research Institute of Changjiang Water Resources Commission; China Institute of Water Resources and Hydropower Research; Yellow River Engineering Consulting Co., Ltd.; Yangtze Three Gorges Survey and Research Institute Co., Ltd.; Yangtze Geotechnical Engineering Corporation. *Code for Rock Tests of Water Resources and Hydropower Engineering*; Ministry of Water Resources of the People's Republic of China: Beijing, China, 2020; p. 265. (In Chinese)
28. Beijing Mining Research Institute, China Coal Research Institute. *Methods for Determining the Permeability Coefficient of Coal and Rock*; Coal Industry Standard: Beijing, China, 1990; p. 5. (In Chinese)
29. Chongqing Institute of Geology and Mineral Resources; Chongqing Juneng Construction Co., Ltd. *General Provisions for Water Quality Analysis of Coal Mine Water*; General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China: Beijing, China; Standardization Administration of China: Beijing, China, 2017; p. 8. (In Chinese)
30. Ji, H.Y.; Wang, W.B.; Xin, Y.J.; Zhang, D.; Gao, Z.; Ren, J. Experimental Study on Acoustic Emission Fractal-Permeability Model of Coal Samples under Hydraulic Coupling. *J. China Coal Soc.* **2024**, *49*, 3381–3398. (In Chinese)

31. Xu, X.Y.; Huangfu, M.N.; Ma, M.T.; Hu, J. Discussion on Strength Deterioration Mechanism of Water-Immersed Coal Samples and Optimization Method for the Design Formula of Water-Resisting Coal Pillars. *Coal Sci. Technol. Mag.* **2024**, *45*, 56–62. (In Chinese)
32. Wessels, D.G.; Malan, D.F. A Limit Equilibrium Model to Simulate Time-Dependent Pillar Scaling in Hard Rock Bord and Pillar Mines. *Rock Mech. Rock Eng.* **2023**, *56*, 3773–3786. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.