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Evaluation of Long-Term Tightness of the Coal Pillar Dam of Underground Reservoir and Protection Countermeasures

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Abstract: The coal mine underground reservoir is an effective facility for mine groundwater utilization in water-deficient and ecologically fragile areas. Usually, the artificial reserved coal pillar is used as the dam of underground reservoir, and little research has been done on its tightness performance. Comsol software is used to simulate the leakage of underground reservoirs in Shendong area, in the western part of China, and the long-term tightness of coal pillar dam under different operation conditions is evaluated. The results show that: (1) When the underground reservoir is not connected with the upper water system, the coal pillar dam has good tightness performance. When they are connected, the leakage of reservoir increased due to the raised water level, and the deeper the burial depth, the greater the leakage amount. (2) When reservoir is pumping and storing water, the leakage is only half of that under constant water pressure storage, indicating that this operation mode is beneficial to the long-term tightness of a coal pillar dam. (3) With the increase of the permeability of a coal pillar dam, the leakage will be aggravated. It is suggested that the permeability of a coal pillar dam should not exceed 1×10^{-15} m^2. (4) The tightness of the coal pillar dam damaged by brine immersion is greatly reduced. With only 3 m of soaking damage distance, the total leakage is twice that of the undamaged one. For a coal pillar dam with poor tightness, some protection countermeasures are proposed to reduce the reservoir water level or improve the anti-seepage performance of a coal pillar dam, so as to ensure the long-term tightness of the dam. This research can provide theoretical support and technical guidance for evaluating the seepage stability of a coal pillar dam in an underground reservoir and strengthening its seepage control.

Keywords: long-term tightness; underground reservoir; coal pillar dam; soaking damage; protection countermeasures

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1. Introduction

In the future, most of China's coal planning areas will concentrate on the western regions where coal resources are abundant, but water resources are scarce, and the ecological environment is fragile [1]. According to statistics, mine water produced by coal mining in China exceeds 8 billion tons yearly, and its utilization rate is only 25%. Therefore, protecting and using mine water is an important issue for coal development in ecologically fragile areas in western China. It is also the basis for supporting regional economic development and ecological environment coordination [2]. The existing mine water disposal methods treat a large amount of mine water and then discharge it to the surface to ensure underground safety. The evaporation loss of a large amount of discharged mine water makes the water resources in this area even more scarce. It has become a key factor restricting the construction of large-scale energy bases and China's westward shift of coal resources development strategy. Traditional coal mining adopts water-retaining methods and technologies, mainly including a water-retaining area division, grouting repair of water-resisting layer, filling mining, or height-limiting mining. On the one hand, these technologies are difficult and costly. On the other hand, they impact production efficiency and the economy. These methods are also implemented in the water-rich areas in the east. However, it is difficult to meet the production demand by implementing coal development in areas with fragile ecology and extremely precious water resources in the west [3–9]. China Shenhua Group, under the leadership of Gu Dazhao, put forward the idea and technical route of storing and utilizing mine water in underground coal reservoirs to protect the precious water resources in western coal mining areas. After years of research and engineering practice, they overcome many technical problems, such as water quantity prediction, reservoir capacity determination, dam design and construction, safe operation of reservoirs and water quality guarantee, etc. and established the technical system of underground coal reservoirs. Furthermore, they successfully built and operated the demonstration project of underground coal reservoirs and finally realized the combination of modern coal mining and mine water resources protection. Currently, a total of 32 underground coal mine reservoirs have been built with a water storage capacity of 31 million m^3, the only underground coal mine reservoir group in the world [10]. In addition, with the completion of the underground coal mine reservoir, peak shaving of renewable energy combined with pumped storage of the underground mine reservoir will gradually become a reality [11–19]. The coal pillar dam of an underground reservoir in western coal mines is in a complex stressful and seepage environment, and its long-term anti-seepage performance and stability are changing and weakening [20]. Around the damage evolution of coal and rock mass under complex coupling conditions, domestic and foreign scholars have conducted more exploration and research [21–23]. Xue [24] studied the gas seepage mechanism in a coal seam based on a coupled model and revealed that the damage significantly impacts the gas extraction of the coal seam. Tang [25] studied the mechanical failure modes and fractal characteristics of coal samples under repeated dry-saturation conditions and used the AE technology to determine the sample failure process's different stages and stress thresholds. Jia Wenqing [26] studied the analysis of coal and rock pyrolysis and the infiltration coupling process and established a mathematical model of coal and rock in-situ pyrolysis and infiltration coupling. Yin and Zhang [27] used the self-developed seepage device to study the mechanism and law of gas migration and enrichment in a deep mining broken coal rock mass. Shi and Meng [28] used theoretical analysis and numerical simulation calculation methods to analyze rock deformation–permeability characteristics and their three-dimensional quantitative relationship. Ma [29–31] found that, as the tectonic stress coefficient is increased, fractures in surrounding rock increase and the seepage grow rapidly. It can be seen from the above research that the previous research on multi-field coupling in coal mines mainly focused on the crack development and damage accumulation of coal rock mass during gas desorption. In contrast, the research on coal pillar dam damage and its seepage control and stability evaluation is still insufficient. The mining life of a mining area is as short as several years and as long as several decades, which leads to the long service life of underground reservoirs in coal mines. In the normal circumstances of an underground reservoir, water is only in the cofferdam of the dam and within the height range of the coal pillar. However, in some cases, the water level will rise sharply when the caving zone or fractured zone is connected with the surface water or the upper aquifer. The sharp increase in water level leads to a great increase in water pressure on the coal pillar dam and the water seepage along the coal pillar dam. Furthermore, in some areas, for example, in the Ningdong area, as the groundwater contains salt, the coal pillar dam is soaking and damaged in the concentrated brine, leading to the increased penetration and the weakened strength of the coal pillar dam [32]. These will undoubtedly affect the structural stability and anti-seepage tightness of the coal pillar dam after long-term service. Therefore, it is crucial to study the seepage characteristics of coal pillar dams under various factors and then put forward corresponding engineering countermeasures for scientifically evaluating and maintaining the long-term safety of underground reservoirs.

Based on the geological conditions and the operational characteristics of underground coal reservoirs in the Shendong area, this paper establishes the seepage model of a coal pillar dam in underground reservoirs. The seepage of the coal pillar dam under the conditions of when the reservoir is connected with the upper water, when the reservoir is under pumping and storing water, and when the coal pillar dam soaking and damaged by concentrated brine are simulated and evaluated. The leakage amount of reservoir and pore pressure distribution in the coal pillar dam under different working conditions are calculated, and the stability of the coal pillar dam is evaluated. Finally, engineering measures for strengthening and seepage prevention of coal pillar dam are proposed.

2. Simulation Scheme

2.1. Basic Information

There are 31 coal mine underground reservoirs in the Shendong area, with a total storage capacity of 3.2×10^7 m^3. The caving-mining ratio is 4:1, and the fracture-mining ratio is 30:1 in this area [8]. According to the field data, the average mining height is 5 m; thus, the height of the caving zone is 20 m, and the height of the fractured zone is 150 m. The caving zone of the reservoir is mainly composed of broken rocks and residual coal cinders, which has a large porosity, about 30% [1]. The fractured zone contains many fractures, but its integrity is higher than that of the caving zone, at about 20%. Because of the tall height of these two zones, the underground reservoir is considered to connect with the upper aquifer and surface water through the fracture. Therefore, the effects of the overlying stratum water and surface water on the underground reservoir can not be ignored. The reservoir's storage capacity is about 1E6 m^3, and the perimeter of a single reservoir is about 2000 m. The fluctuation of the water level in the reservoir causes the change in water pressure, and the calculation formula of water pressure is given as Equation (1):

$$P_w = \rho_w g h \tag{1}$$

where, P_w is the water pressure at the bottom of the reservoir, MPa; ρ_w is the density of water in the reservoir, kg/m^3; g is the gravity constant, taking 10 m/s^2; h is the water level height, m.

2.2. Seepage Calculation Model

Combined with the operation situations of coal mining and underground reservoirs, a two-dimensional geological model of the underground reservoir in a coal mine is established, as shown in Figure 1. This model has a height of 155 m and a length of 300 m. The upper strata of the underground reservoir are the caving zone and fractured zone, while the coal pillar dam, the empty roadway, and the mining seam are in the horizontal direction. The coal pillar dam has a thickness of 20 m and a height of 5 m; it is the main research object of this paper. During simulation, the water in the reservoir seeps out from the coal pillar dam, the reservoir side wall of the coal pillar is set as the water inlet, and the empty roadway side wall is set as the outlet.

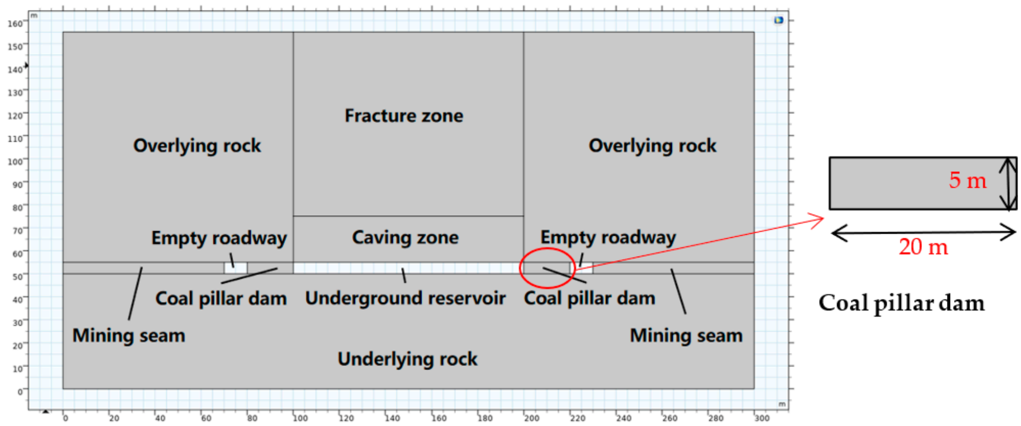


Figure 1. 2D geological model of the underground reservoir and coal pillar dam in the coal mine.

2.3. Theoretical Model of Seepage

In this paper, the Darcy seepage module of Comsol software is used for simulation. All the surrounding rocks of the reservoir are considered as the porous media water storage models. It is assumed that the pressure gradient is the major driving force and the flow is mostly influenced by the frictional resistance within the pores. Therefore, water seepage in rock stratum conforms to Darcy's law. According to the continuity equation of Darcy seepage, Equations (2)–(4) are given as follows:

$$\frac{\partial}{\partial t}(\Phi\rho) + \nabla(\rho u) = Q_m \tag{2}$$

$$\frac{\partial}{\partial t}(\Phi\rho) = \rho S \frac{\partial P}{\partial t} \tag{3}$$

$$S = \Phi\beta_g + (1-\Phi)\beta_S \tag{4}$$

Considering the effect of gravity, the fluid velocity is:

$$u = -\kappa(\nabla P + \rho g \nabla h)/\mu \tag{5}$$

The model boundary is set as the no-flow boundary, that is:

$$-n \cdot \rho u = 0 \tag{6}$$

where, Φ is the porosity of the rock, 1; ρ is the fluid density, g/cm^3; u is the fluid velocity, cm/s; Q_m is the mass source, kg; P is the fluid pressure, MPa; μ is the fluid viscosity, mPa·s; κ is the rock permeability, 1×10^{-12} m^2; S is the water storage coefficient of rock; β_g is the fluid compression ratio, and β_s is the rock skeleton compression ratio.

Furthermore, considering that the mining seam is in its mining period and the mining area is not connected with the reservoir area, the boundary pressure of the empty roadway is set to 1 atmosphere. In our simulation model, the initial pore pressure of the dam is set as 1 atmosphere (0.1 MPa), and the data of porosity and permeability are specified in Table 1. The density of water is $1\text{g}/\text{cm}^3$, and the service life of the reservoir is set as 30 years.

Table 1. Porosity and permeability parameters of rock formation.

Rock Stratum	Porosity (%)	Permeability (m^2)
Overlying strata	7	2×10^{-17}
Coal pillar dam body	10	1×10^{-15}
Underlying strata	6	1×10^{-17}

2.4. Working Conditions' Settings

Considering the geological environment of underground reservoirs in coal mines, the underground reservoirs are primarily built within 300 m. The construction and operation of deeper reservoirs are complicated and cost more, so they will not be considered. To analyze the coal pillar dam's sealing performance and operation safety, several working conditions have been considered in this paper. They are as follows:

1. When the underground reservoir is connected with the upper aquifer and the surface water system, both the caving zone and fractured zone may be filled with water. The water level of reservoir increased, which will cause the coal pillar dam to bear higher water pressure.
2. Periodic fluctuation of water level and pressure caused by pumping and storing water in reservoirs. After the underground reservoir is built, the water level gradually decreases during the water use period while increasing during the water storage period. If the underground reservoir is used for a pumped storage power station in the future, it will cause more frequent fluctuation in water level.

3. Coal pillar dams are damaged due to the brine immersion, the mining disturbance, and the long-term service damage. For example, in some mining areas of western coal mines, where salinity of groundwater is high, long-term immersion will damage the reservoir side of the coal pillar dam and then promote the development of cracks and increase its permeability.

By using Comsol software, the tightness of the underground reservoir is simulated. The long-term tightness of coal pillar dam under different conditions is evaluated from the perspectives of the leakage range of water, the distribution of pore pressure and the leakage amount of water.

3. Constant Pressure Water Storage

3.1. Basic Situation Setting

This working condition considers the situation when underground reservoirs are at different stratum depths, and are connected with the upper aquifer or surface water system through fissures. The subterranean depths of coal mine reservoirs are 100 m, 200 m, and 300 m, respectively.

Considering the shallow depth of the reservoir, the caving zone and fracture zone are set to be connected with the surface. In extreme cases, the underground reservoir is connected with the surface pool. Assuming that the underground reservoirs with different depths are all connected with the surface, then the calculated water pressures in the reservoirs are 1.3 MPa, 2.5 MPa, and 3.7 MPa, respectively.

3.2. Simulation Results of 100 m Depth

The seepage situation of coal pillar dam within 30 years is simulated under the depth of 100 m, water pressure in the reservoir side of dam is constant (about 1.3 MPa in this condition),while the initial pore pressure of dam is 0.1 MPa. The simulation results and analysis are as follows:

(1) Leakage range

Figure 2 shows the evolution of leakage range and streamline in the coal pillar dam over 30 years. The outermost white pressure contour line is 0.1 MPa, representing the boundary of the leakage range. The red line with an arrow indicates the streamline of water, and the arrow points to the outflow direction of the water. It can be seen that the leakage range in the coal pillar dam developed rapidly in the early stage (0–10 years) and gradually slowed down in the later stage. Moreover, because of the effect of gravity, the leakage range in the lower part of the coal pillar is more extensive. The boundary of the leakage range in the coal pillar dam presents an inverted "S" curve with a narrow upper part and a wide lower part. It can be found that, due to the high osmotic pressure of water near the reservoir, gravity has little influence on the distribution of the pressure contour line, and it shows a vertical distribution. On the contrary, the osmotic pressure is very small at the area of the leakage boundary far from the reservoir, and gravity significantly influences the contour line distribution, which causes the inverted "S" shape.

(2) Pore pressure in the coal pillar dam

The pore pressure distribution in the coal pillar dam in 0–30 years is calculated, as shown in Figure 3. It can be found that, with the increase of leakage time, the pore pressure at the same position gradually increases, indicating that the water leakage in the surrounding rock is getting worse. At the same time, during the whole 30-year water storage period, the pore pressure of surrounding rock showed a rapid increase in the early stage and a slow increase in the later stage. It is worth noting that, in the past 30 years, the areas with high pore pressure are always concentrated in the regions with a leakage distance of less than 8 m, indicating that the water leakage of the reservoir is still under control.

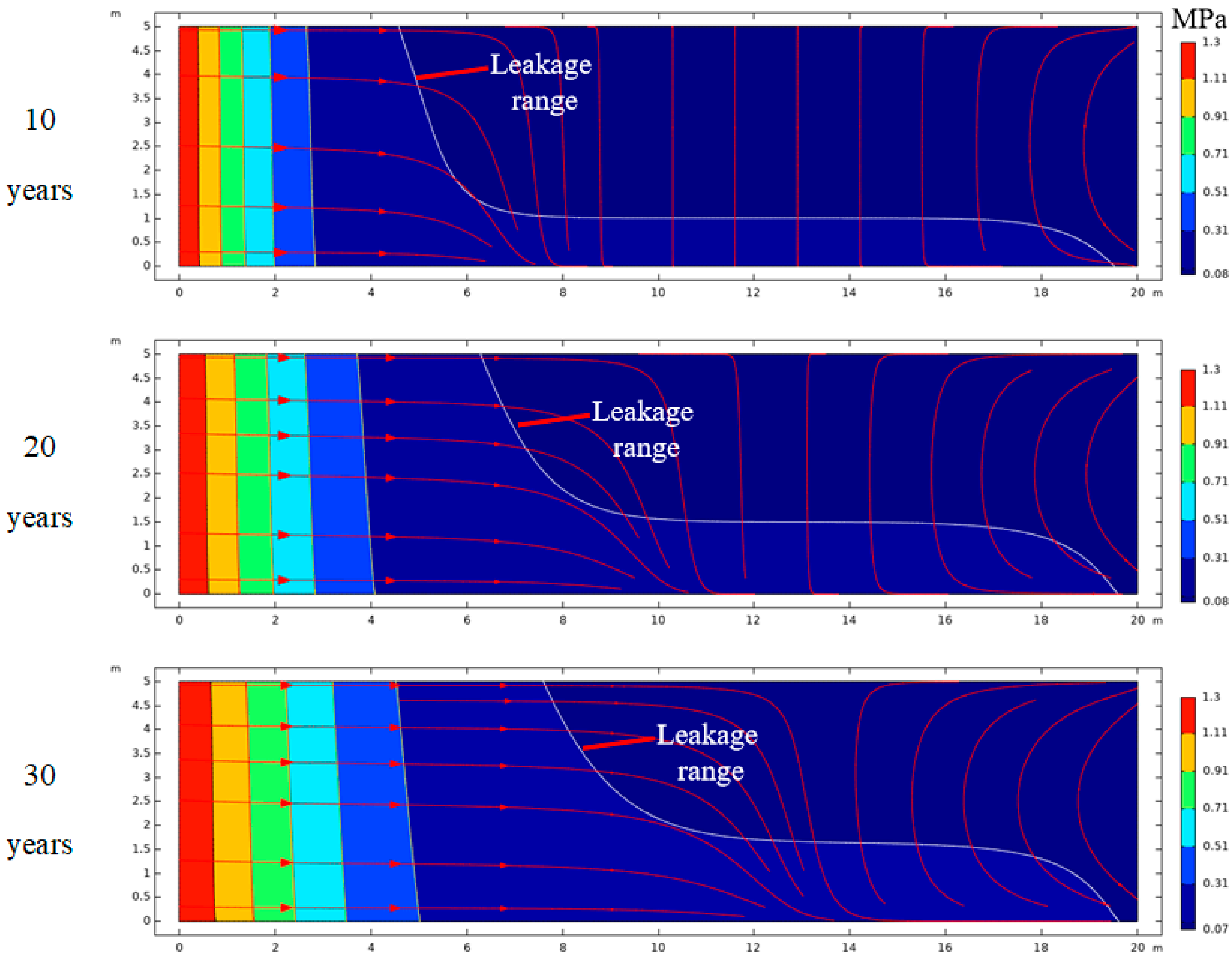


Figure 2. Evolution of leakage range in the coal pillar dam with the depth of 100 m (Unit: MPa).

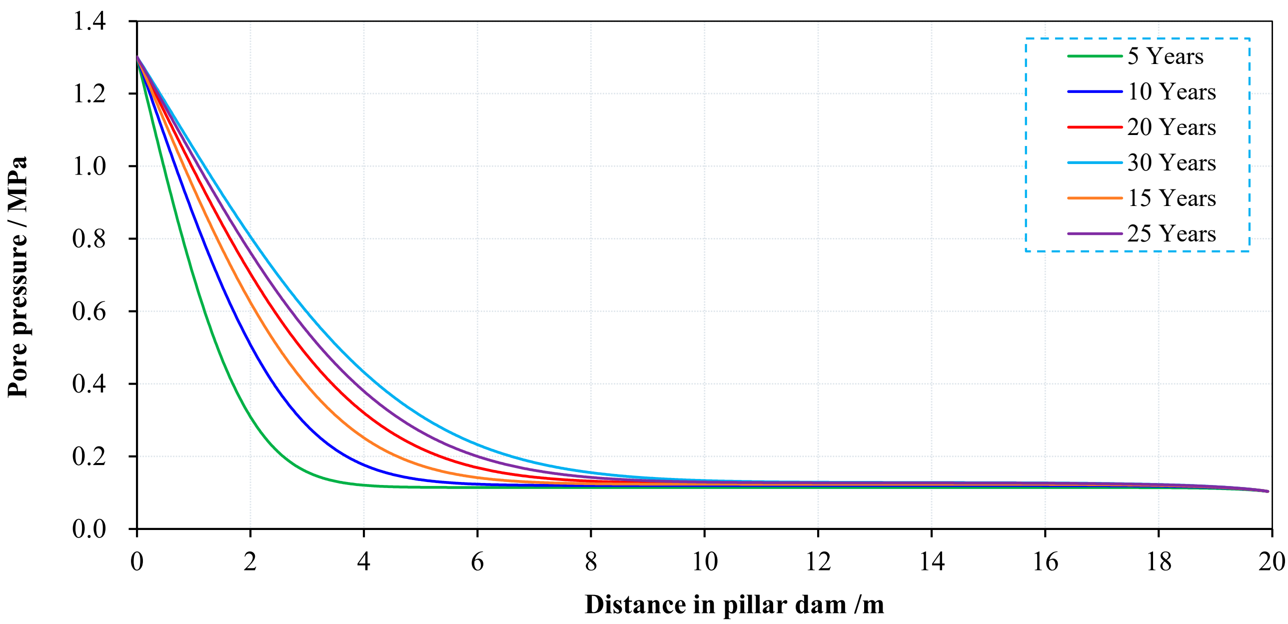


Figure 3. Distribution of pore pressure in the coal pillar of the underground reservoir with a depth of 100 m.

(3) Cumulative leakage amount

The cumulative leakage amount of two cases is calculated, that is, when the reservoir is not or is connected with the ground, as shown in Figure 4. It can be found that, when water is stored normally and there is no water-pressure from the upper water system, the accumulated leakage after 30 years of service is only 4.82×10^5 m^3 (the average annual leakage is 1.49E4 m^3, and the average daily water leakage is 40.93 m^3). However, the leakage amount increased significantly when water was connected with the surface. The accumulated water leakage in this situation is 3.67×10^6 m^3 (1.22×10^5 m^3per year and 335.2 m^3 per day), which is 8.19 times of the former case; this will bring some trouble to dam seepage prevention. For a reservoir with a water storage capacity of 1×10^6 m^3, the average annual leakage rate has reached 12.2% of the total water storage capacity at a depth of 100 m. It also can be seen that, when water is stored with pressure, the leakage in the early stage increases rapidly, but the upward trend of the leakage in the later stage gradually slows down. It indicates that, when the underground reservoir is connected with the upper aquifer or the surface water system, the increase of water pressure will significantly impact the seepage control of the reservoir, and measures such as pumping water should be taken to reduce the water level to control the leakage as soon as possible.

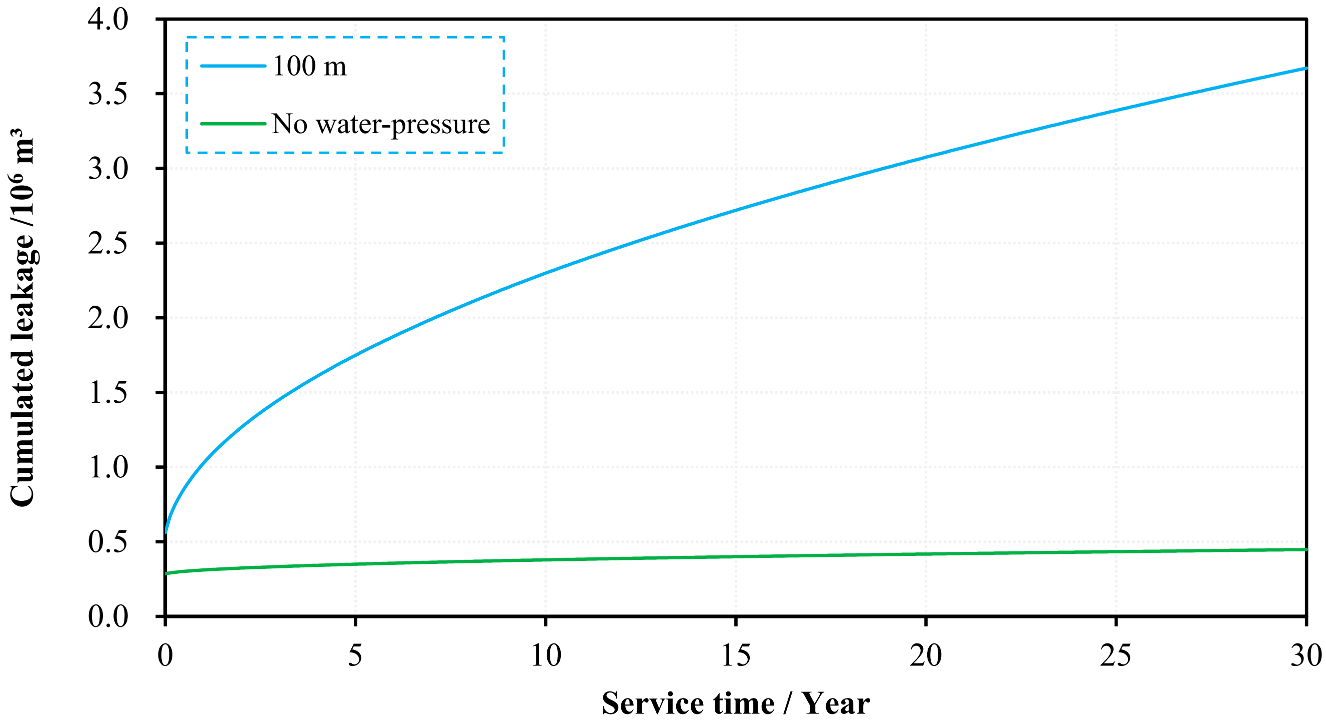


Figure 4. Cumulative leakage in the coal pillar of the underground reservoir.

3.3. Comparison of Different Depths

In order to study the tightness performance of coal pillar dams with different burial depths, the numerical simulation of 200/300 m buried depth was carried out, on the basis of 100 m buried depth, by increasing the water pressure and keeping the other conditions unchanged.

(1) Comparison of leakage range

In this part, three working conditions of the underground reservoir with a depth of 100/200/300 m are compared. Figure 5 shows the seepage range of the coal pillar dam after 30 years of service.

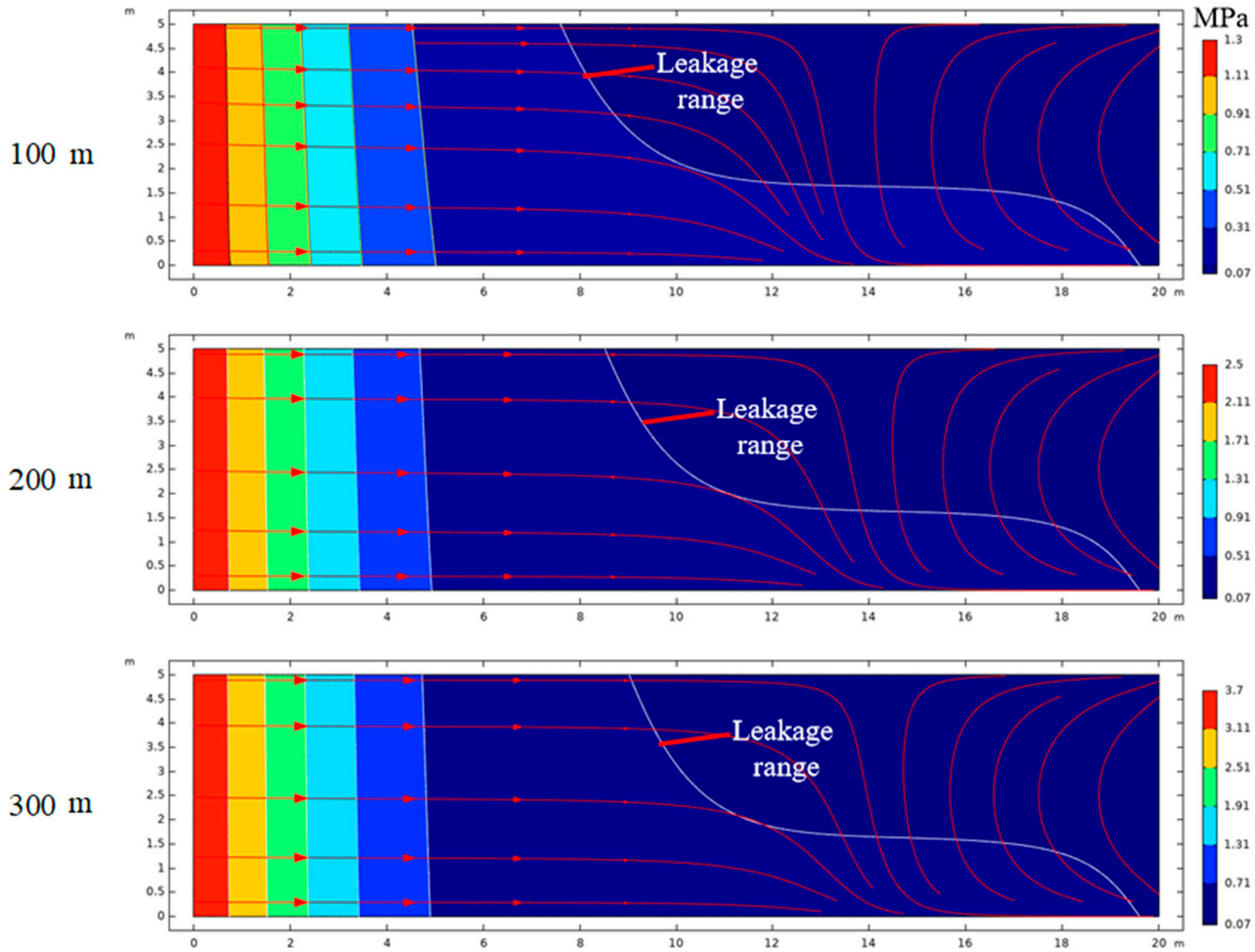


Figure 5. Distribution of seepage range in the coal pillar dam with different depths (Unit: MPa).

It can be found that the seepage trend of water in the coal pillar is consistent in some respects. Areas of high pore pressure were mainly concentrated on the reservoir side, and the leakage range was an inverted "S" shape. However, deeper buried depth means larger water pressure, with the increase of depth, both the seepage range and the range of the high-pressure area in the coal pillar increased.

Moreover, when the pore pressure on the reservoir side is too enormous, the coal pillar dam will be softened by brine soaking. Thus, its bearing capacity will be significantly reduced or even lost (further evaluation will be done with the pore pressure distribution). Therefore, with the increase of depth, it can be considered to appropriately increase the width of the coal pillar dam or take necessary seepage control measures on the reservoir side and increase drainage measures on the roadway side.

(2) Comparison of pore pressure

Figure 6 shows the pore pressure distribution in the coal pillar dam after the reservoir has been in service for 30 years. It can be seen that, with the increase of depth, the pore pressure in the pillar increases rapidly, and its direct consequence is to aggravate the softening damage of the pillar. Therefore, when the depth of the reservoir is considerable, the coal pillar dam not only needs a larger thickness to bear higher stratum pressure but also needs a surplus width to cope with the damage of higher pore pressure to the coal pillar dam body.

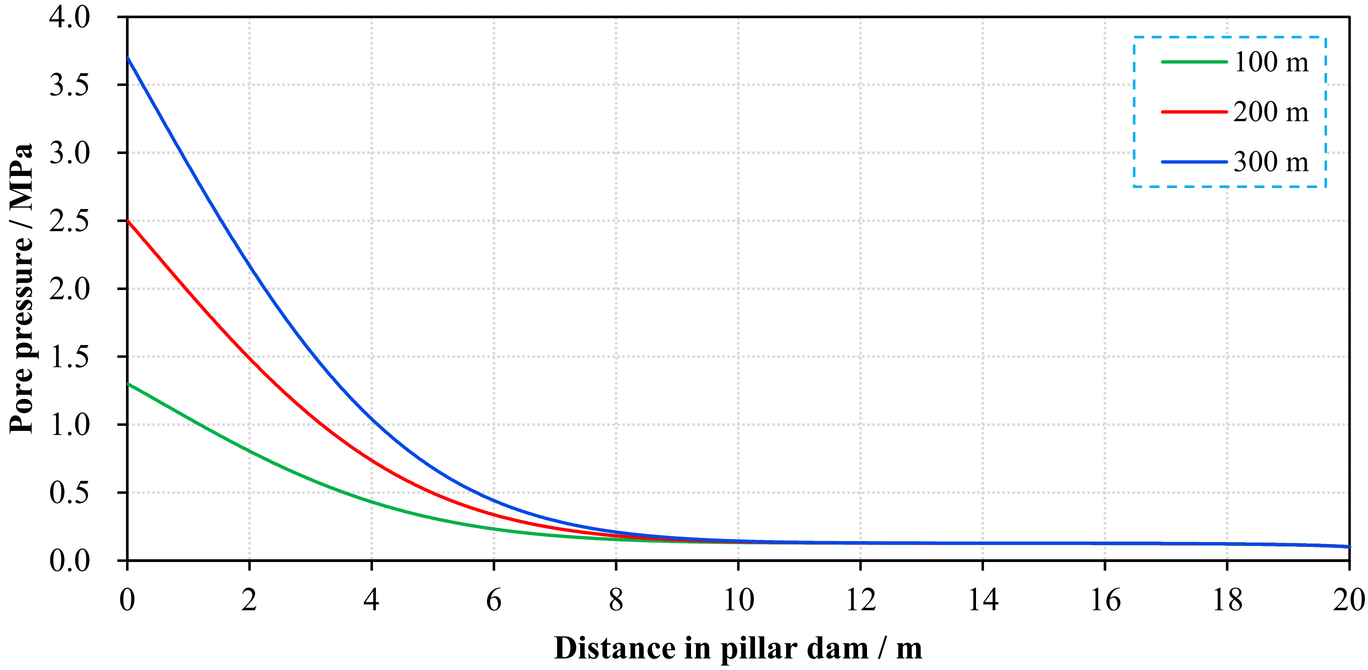


Figure 6. Comparison of pore pressure in the coal pillar dam body under different depths.

Generally, the strength of coal rock is low when the pore pressure of the coal pillar dam near the reservoir side increases rapidly with the increase of depth. According to the effective stress theorem:

$$\sigma_e = \sigma - \beta \cdot \sigma_{pp} \tag{7}$$

where σ_e is effective stress; β is Boit coefficient; for rock material, it usually ranges within 0.5–1.0; σ is total stress; and σ_{pp} is pore pressure of the fluid in rock.

As we all know, due to the erosion of pressurized water (usually high-concentrated brine), the coal matrix will be softened, and cracks and fissures may propagate, weakening the rock strength. As a result, the effective bearing area of the pillar dam will be decreased, and, consequently, the stress in the pillar dam will be increased. If the high water pressure is in the dam, the effect of water leakage and coal softening should be considered.

(3) Cumulative leakage amount

The cumulative leakage under different depths is calculated and plotted in Figure 7. It can be seen that the cumulative leakage in cases of 100/200/300 m is 3.67 million m^3, 7.39 million m^3, and 11.05 million m^3, respectively. Thus, the average annual leakage is 1.22×10^5 m^3, 2.46×10^5 m^3 and 3.68×10^5 m^3, respectively, and the average yearly leakage rate is 12.2%, 24.6%, and 36.8%, respectively. Moreover, the moderate daily leakage is 335 m^3, 675 m^3, and 1010 m^3, respectively. As the depth increases from 100 m to 300 m, the water leakage rises significantly, nearly linearly increasing with the depth. If the underground reservoir is under a high water level for a long time, it will be difficult for the coal pillar dam to meet the anti-seepage requirements. Therefore, the deeper the reservoir is, the more water level detection should be strengthened. If a higher water level is found, pumping measures should be taken in time to ensure the safety of the coal pillar dam.

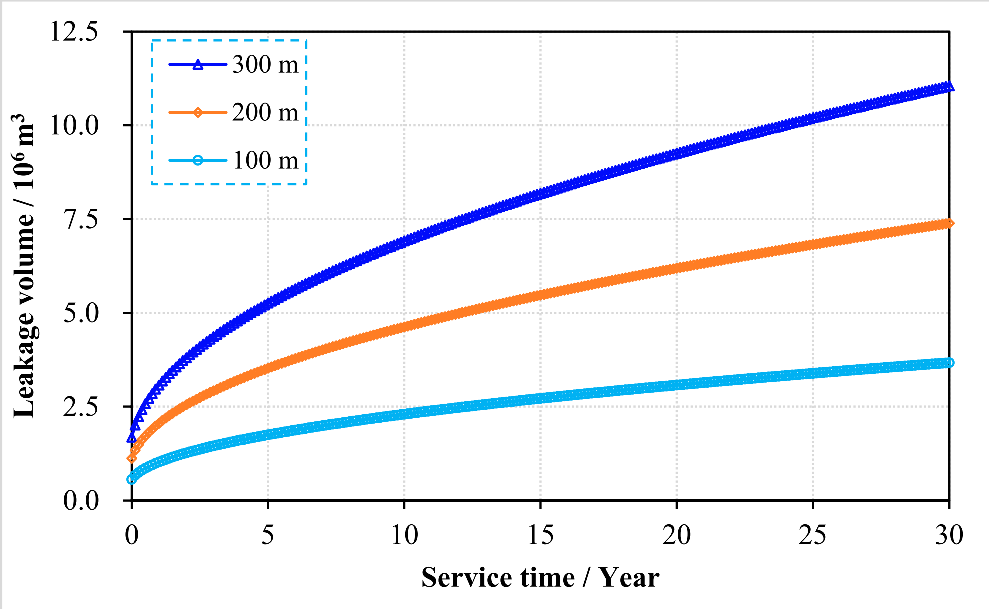


Figure 7. Accumulated leakage volume in coal pillars under different depths.

4. Water Pumping and Storage

Section 3 has considered an extreme working condition. In a more realistic situation, mine water will be injected into or pumped out from the reservoir according to the use of water resources in the mining area. When the mine water is stored in the reservoir, it will be filtered and purified by forming cracks and residual coal, thus improving the water quality. After that, the water can be pumped out from the reservoir and used for surface coal washing or other industrial purposes. Therefore, in the actual service period of the reservoir, the reservoir will often experience water pumping and storage operations. The water leakage range, pore pressure distribution, and cumulative leakage amount in the coal pillar dam under this conditions are studied.

In this part, the reservoir works with a depth of 300 m, and the designed frequency of pumping and storing is four times/year, with each cycle lasting for three months. The water pressure fluctuates linearly between 0.1 MPa and 3.7 MPa, and the setting of rock parameters is consistent with that of constant pressure water storage.

4.1. Pore Pressure Distribution

The pore pressure distribution in the coal pillar dam within 30 years of reservoir service is drawn, as shown in Figure 8. It can be seen that the pore pressure distribution inside the coal pillar dam is quite different from that under constant pressure. Overall, the pressure still increases with the service life, but the increase is slight. The range of high pore pressure on the reservoir side of the dam is minimal (<0.4 m), and the pore pressure drops rapidly (from 3.5 MPa to 1.5 MPa). In the other range (0.4 m–6 m), the pore pressure drops slowly from 1.5 MPa to 0.3 MPa. Beyond 6 m, the pore pressure remains low for 30 years, almost unaffected. Under periodic water pumping and storage, due to the backflow and depressurization of water, the pore pressure in the dam will be significantly reduced, thus having no significant impact on the coal pillar dam. Therefore, for underground reservoirs, periodic operation of pumping and storing water is recommended, which can not only give full play to the water storage value of reservoirs but also maintain the safety of coal pillars. In addition, the pumping-storage operation of underground reservoirs in the western region can also be combined with the construction of pumped storage power stations with peak shaving of renewable energy to exert the value of coal mine goaf further.

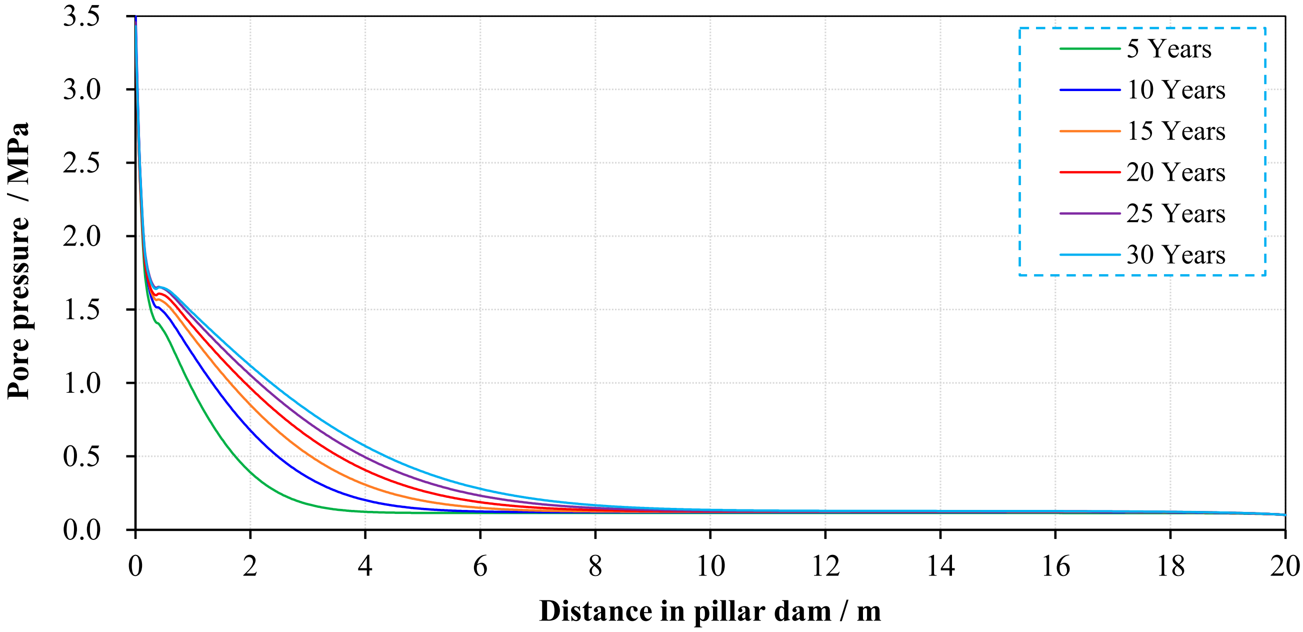


Figure 8. Distribution of pore pressure in the pillar during 30 years of operation.

4.2. Cumulative Leakage

Furthermore, the water leakage during pumping and storage is analyzed, and the accumulated water leakage data after 30 years of service is calculated, as shown in Figure 9. It can be seen that the cumulative leakage in 30 years increases gradually with the service time, and in about the first ten years, it increases rapidly, but the growth rate tends to slow down. In about 10–30 years, it shows a steady trend. Within 30 years, the cumulative leakage is 5.77×10^6 m^3 (only 51.9% of that under constant pressure), the annual average leakage is 1.92×10^5 m^3, and the average daily leakage is 526.9 m^3. Once again, it is confirmed that the water pumping and storage operation can not only give full play to the function of water diversion and water purification of the reservoir, but also effectively reduce the water leakage of the reservoir.

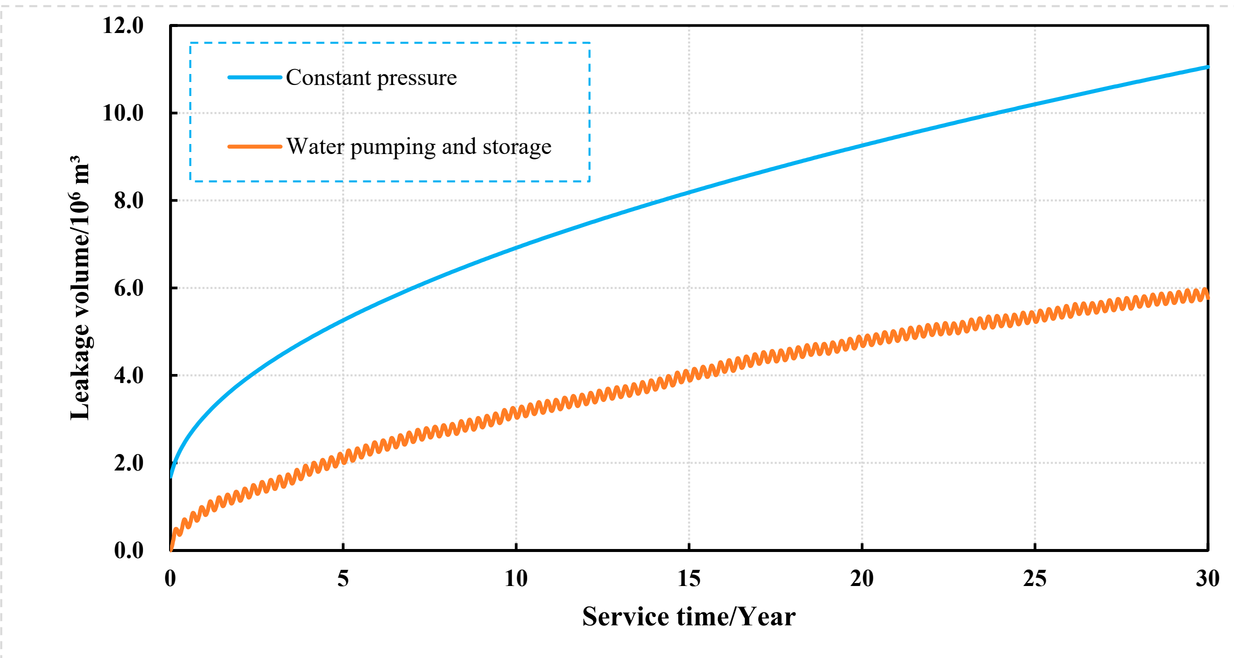


Figure 9. Cumulative leakage of reservoir with water pumping and storage.

5. Influence of Coal Pillar Dam Performance

5.1. Different Permeability of Coal Pillar

Considering different properties of coal seams and mining disturbances, the coal pillar dam has different permeability. The anti-seepage and sealing properties of different conditions of coal pillar dam permeability are analyzed through simulation analysis. The selected reservoir is located at a buried depth of 300 m, and the permeability of the coal pillar dam is 1×10^{-14} m^2, 1×10^{-15} m^2, 1×10^{-16} m^2, and 1×10^{-17} m^2, respectively. Constant water storage is considered, and other parameters of the model are set as unchanged. The leakage range, pore pressure distribution, and cumulative leakage of coal pillar dam in 0–30 years are calculated.

(1) Leakage range

Through the analysis of simulation results, the water seepage range and streamline of the coal pillar dam under different permeability conditions are obtained, as shown in the following Figure 10. When the permeability of the coal pillar dam is high (1×10^{-14} m^2), the water leakage range in the coal pillar dam is enormous, and the streamline is almost straight, which indicates that a large amount of water leakage is out from the reservoir through the coal pillar dam. Because of the high velocity and pore pressure, the effect of gravity on water seepage is almost negligible. Furthermore, the coal pillar dam at this time cannot seal the reservoir effectively. When the permeability of the coal pillar decreases to 1×10^{-15} m^2, 1×10^{-16} m^2, and 1×10^{-17} m^2 after 30 years of operation, the leakage range in the coal pillar dam is about 14 m, 4 m, and 1 m, respectively. As the leakage range is smaller than the width of the dam, it is indicated that the water leakage in the dam is controllable.

To further analyze the influence of permeability on the stability of the coal pillar dam, the distribution of pore pressure was drawn, as shown in Figure 11. It can be seen that, when the permeability is as high as 1×10^{-14} m^2, the pore pressure in the coal pillar dam is linearly distributed, indicating that a stable laminar flow has been formed inside. The flow direction is mainly horizontal, and the flow rate is also significant. However, when the permeability decreases to 1×10^{-15} m^2, the pore pressure at the same distance is greatly reduced. When the permeability drops to 1×10^{-16} m^2 and 1×10^{-17} m^2, the pore pressure drops rapidly in a short range (<2 m), and the flow direction is mainly controlled by gravity, and both the velocity and flow rate are minimal.

(2) Cumulative leakage amount

To quantify the influence of permeability on water leakage, the relationship between permeability and cumulative leakage amount after 30 years of service is analyzed, as shown in Figure 12. It can be seen that the 30-year cumulative leakage of coal pillars with the permeability of 1×10^{-14} m^2 is 4.59×10^7 m^3, the average annual leakage is 1.53×10^6 m^3, and the average daily leakage is 4.19×10^3 m^3. When the permeability of the coal pillar is high, the water leakage of the dam body is severe, and the function of seepage prevention and waterproofing can no longer be achieved. However, when the permeability drops to 1×10^{-16} m^2 and 1×10^{-17} m^2, the cumulative water leakage in 30 years is 3.19×10^6 m^3 and 9.39×10^5 m^3, and the average annual leakage is 1.05×10^5 m^3 and 3.13×10^4 m^3, with a significant decline.

With the increase of permeability, the main hazards are:

(1) A large amount of water leakage will bring trouble to the underground working face, especially when the leakage is high. Secondary disasters caused by water leakage should be prevented.
(2) High pore pressure in the coal pillar will decrease the effective stress, leading to the local spalling and crushing, and reducing the effective pressure-bearing area.
(3) Large coal pillar permeability will cause the loss of tiny powder and particles in the coal body due to the high flow velocity and strong hydrodynamic force. It may result in the phenomenon of "flowing soil" and "piping"; moreover, the sudden collapse of coal pillars when it develops to a certain extent.

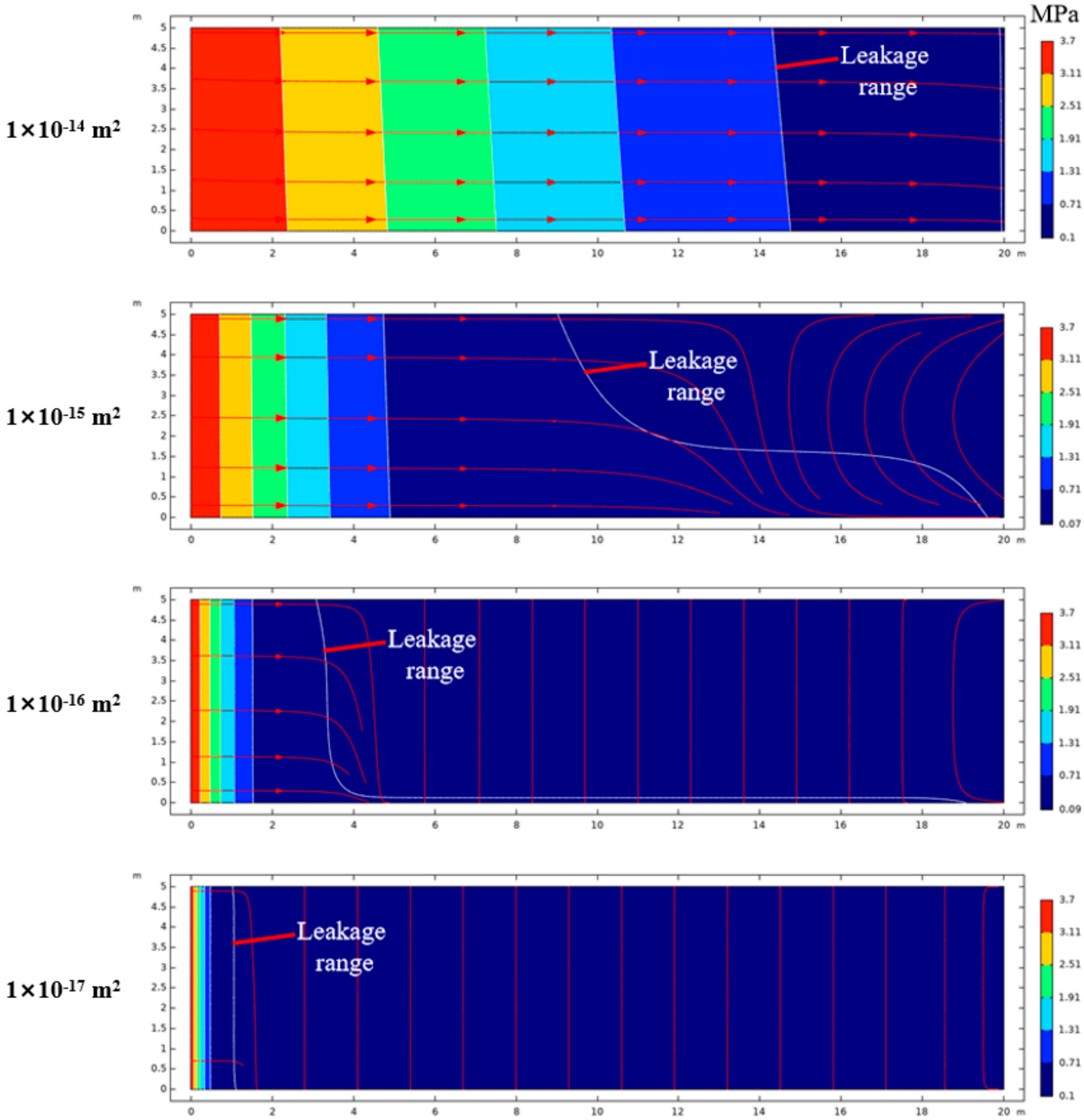


Figure 10. Leakage range and streamlining the distribution of coal pillar dam with different permeability.

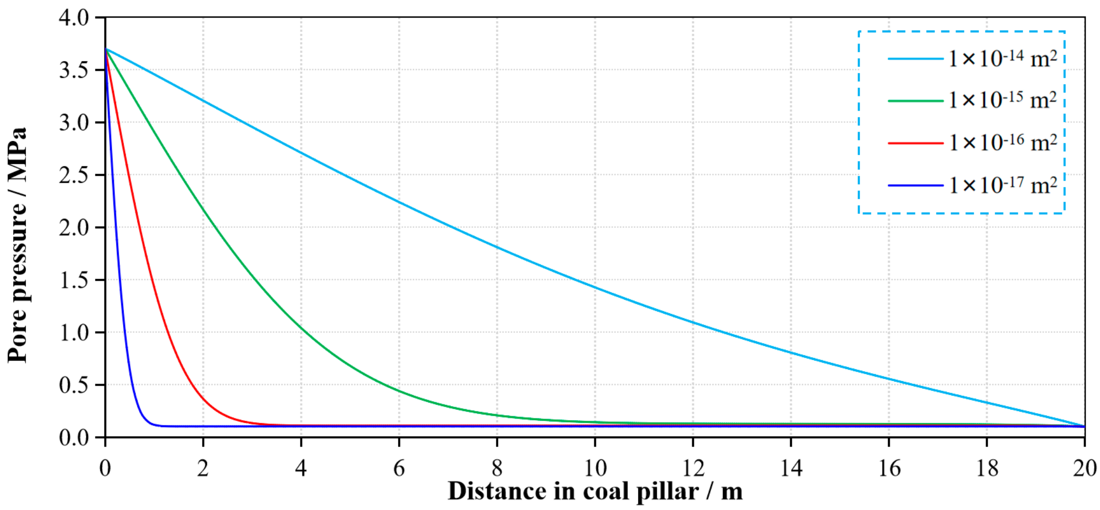


Figure 11. Pore pressure distribution of the coal pillar dam under different permeability.

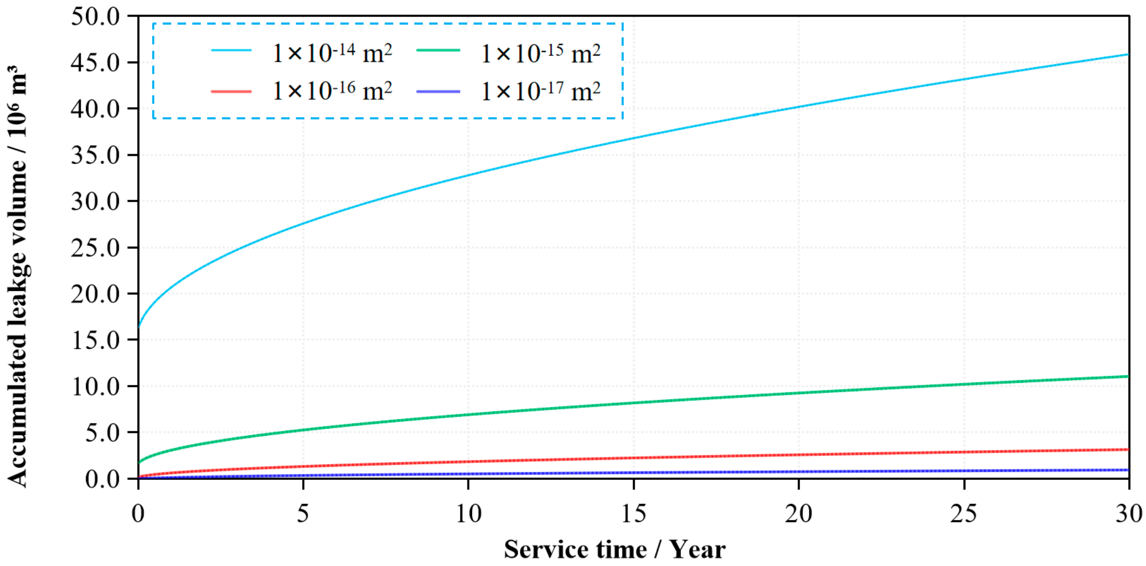


Figure 12. Cumulative water leakage amount of the coal pillar dam with different permeability.

Therefore, when selecting a coal seam for the underground reservoir, try to choose the one with shallow depth and low coal permeability, thus effectively improving the anti-seepage performance of coal pillar dam. It is suggested that the allowable permeability of the coal pillar dam should not be higher than 1×10^{-15} m^2.

5.2. Damage Zone in the Coal Pillar

In practical work, with the influence of reservoir service, intense brine immersion, and adjacent mining, the coal pillar dam will be damaged, and the permeability will be enhanced. However, the degree of this damage is often severe on the surface of the dam body and gradually decreases with the increase of leakage distance. As a direct result, the closer to the adjacent water (air) surface, the greater the damage degree and the higher the permeability of the coal pillar. Combined with the distribution characteristics of pore pressure in the coal pillar, the permeability of the coal pillar dam under this condition is divided, as shown in Figure 13.

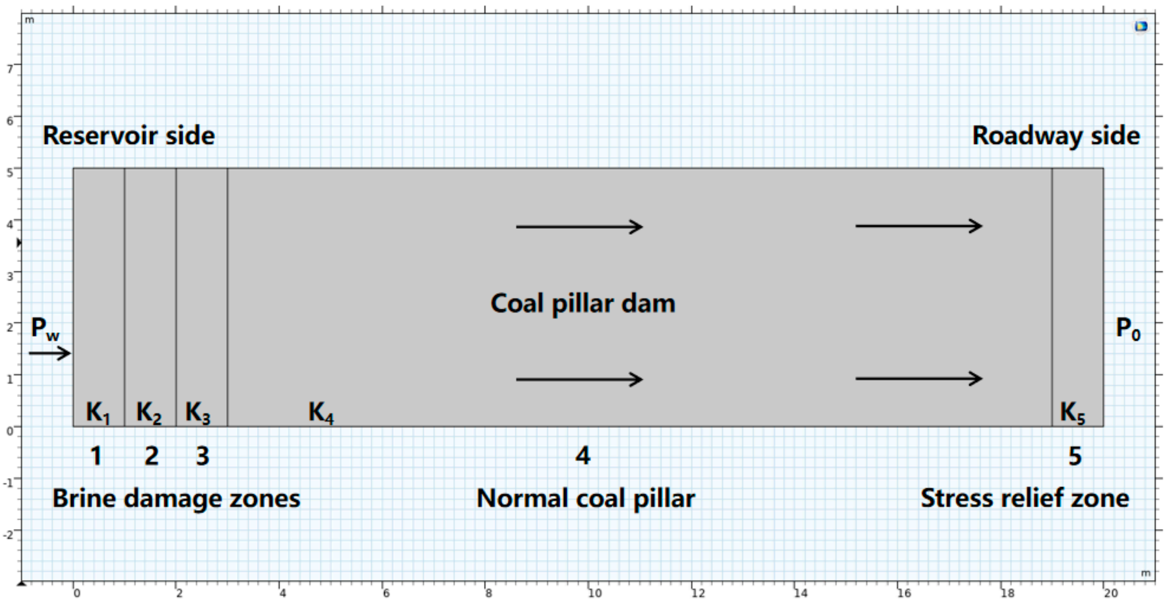


Figure 13. Schematic diagram of damage zone distribution in the coal pillar dam.

Different permeability zones in coal pillars are set up, and the water seepage in coal pillar dam under this condition is simulated. The damage zone near the reservoir has the highest permeability, $K_1 = 1 \times 10^{-14}$ m^2. Then, the permeability gradually decreases, where $K_2 = 7.5 \times 10^{-15}$ m^2 and $K_3 = 5 \times 10^{-15}$ m^2. Each damage zone has a thickness of 1 m. Due to stress release, there is a specific damage zone near the empty roadway. Its permeability is set to $K_5 = 2.5 \times 10^{-15}$ m^2, with a thickness of 1 m. The permeability of the intact coal rock in the middle part is $K_4 = 1 \times 10^{-15}$ m^2, and its thickness is 16 m. Taking the operation of pumping and storing water as the background, the cycle is four times per year, the operation time is 30 years, the water pressure is between 0.1 MPa and 3.7 MPa, the brine density is 1.2 g/cm^3, and the other parameters are unchanged.

(1) Leakage range

As seen in Figure 14, the leakage range of water in the coal pillar dam increases with time, increasing rapidly in the early stage (the first 10 years) and levelling off in the later stage. During the first ten years, the leakage range increased about 10 m, and during the last 20 years, only about 6 m increased. The boundary of the leakage range shows an inverted "S" curve with a narrow upper part and a wide lower part.

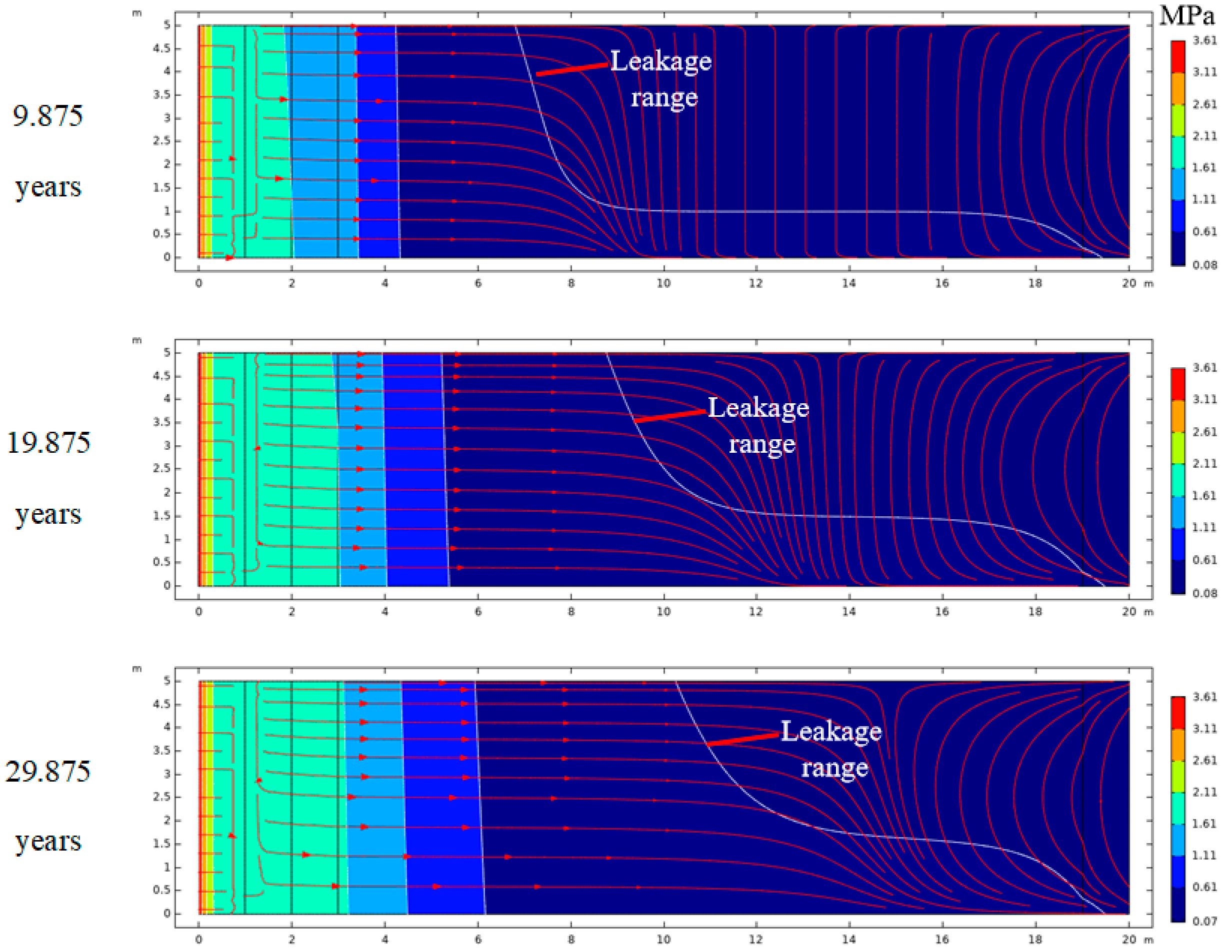
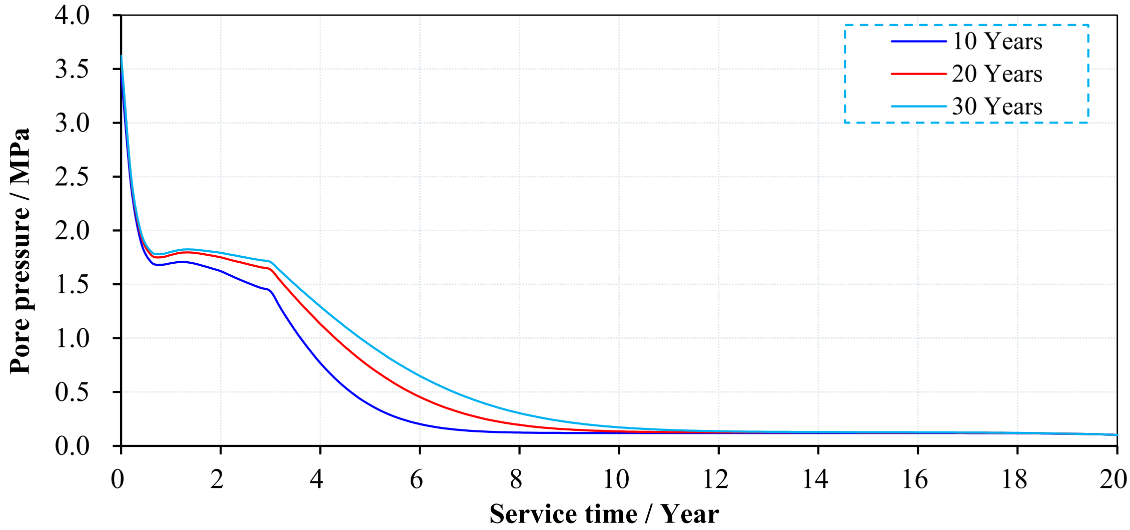


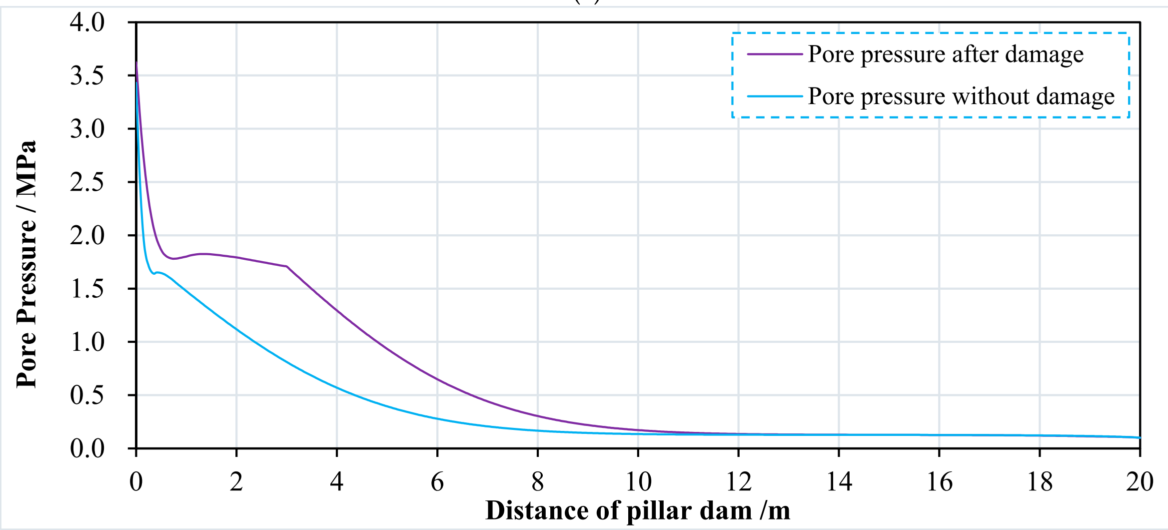
Figure 14. Changes of leakage range with time.

(2) Pore pressure distribution

The distribution characteristics of water pore pressure in the coal pillar dam have been analyzed, as shown in Figure 15a. It can be seen that, when there is a damaged zone with high permeability in the coal pillar dam, the water pore pressure drops rapidly; then, a slow-down platform appears and then drops until it reaches a low value. Two pore pressure curves of damaged and undamaged coal pillars are plotted in Figure 15b. Due to the larger permeability in damaged zones, the pore pressure in the same position of the dam is higher than that in undamaged zones. Although the width of the damaged zones near the reservoir side is only 3 m, the pore pressure still affects the lateral depth of 3–10 m. Therefore, when the coal pillar is damaged, its influence on pore pressure will reach about three times the range of the damaged zone. Outside this range, the pore pressure curves coincide and have no significant effect.



(**a**)



(**b**)

Figure 15. Distribution of pore pressure in the coal pillar dam. (**a**) pore pressure distribution of the coal pillar dam with damaged zones at different times; (**b**) comparison of pore pressure distribution of the damaged and undamaged coal pillar dam.

(3) Cumulative leakage amount

The cumulative water leakage curve of a damaged and undamaged coal pillar dam within 30 years of service is drawn, as shown in Figure 16. It can be seen that, after the coal pillar is damaged, the accumulated water leakage in 30 years is 1.15×10^7 m^3, and the average annual leakage is 3.83×10^5 m^3/ year. The cumulative leakage of undamaged coal pillar in 30 years is 5.77×10^6 m^3, and the average yearly leakage is 1.92×10^5 m^3. That is to say, when the coal pillar is damaged in a small area (only 3 m), the cumulative leakage of the coal pillar dam has nearly doubled (99%). Therefore, during the construction and operation of the reservoir, we should pay close attention to the damage to the coal pillar dam near the reservoir side to prevent the leakage from increasing greatly after its loss.

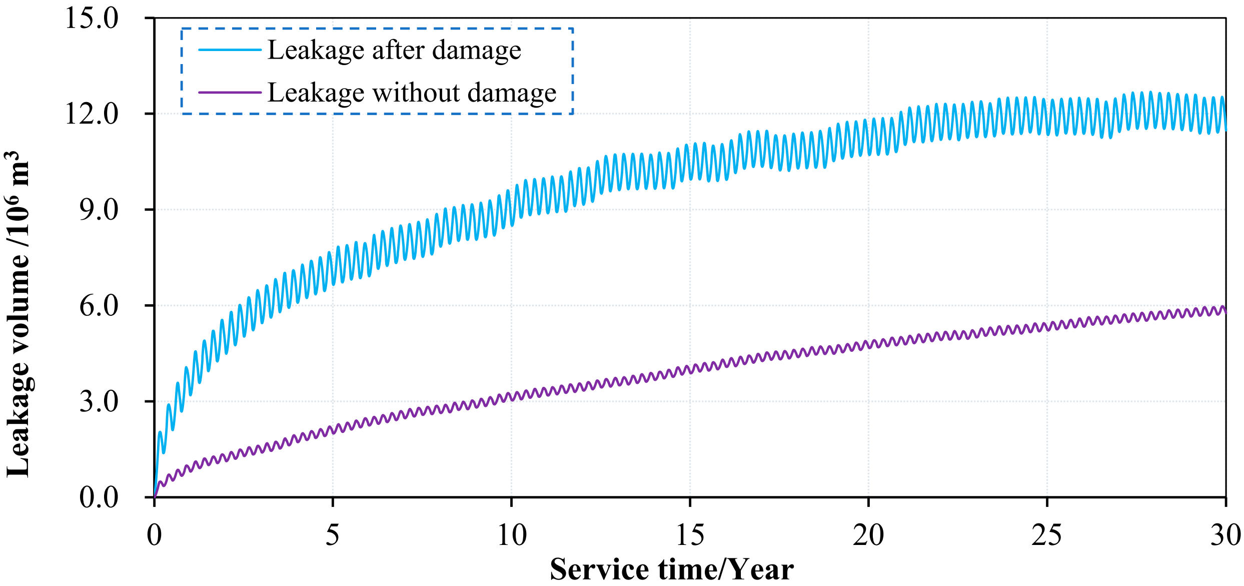


Figure 16. Comparison of cumulative leakage volume between the damaged and undamaged coal pillar dam.

6. Discussion and Application

It can be seen from the above research that several factors affect the leakage of the coal pillar dam. The following discussion and application analysis are given to the previous study:

(1) When the reservoir is not connected with upper water system, the leakage is minimal, and the average annual leakage only accounts for 1.5% of the total water storage. Once they are connected, water pressure in the reservoir increased rapidly, significantly increasing the leakage. When the water pressure is 100 m water column height, the leakage will increase by more than seven times, and when the water pressure is 300 m water column height, the leakage will increase by 23.66 times. Therefore, detecting and controlling the water pressure change in the reservoir area is crucial, which is the key to preventing leakage. Once the water pressure is too high, priority should be given to pumping and depressurizing the reservoir when using water in the mining area. Although the fracture zone has adverse effects on dam leakage prevention, it is equivalent to gathering more water resources for utilization, and the deeper the depth, the greater the collected water amount should be. Therefore, the problem of reservoir depth should be treated dialectically.

(2) Permeability of coal pillar dam is also an essential factor affecting the leakage. It can be seen from the above simulation that the higher the permeability of the coal pillar dam, the greater the leakage. It is suggested that the coal seam with low permeability and complete structure should be selected as far as possible to build the reservoir to ensure the anti-seepage performance of the reservoir. At the same time, for coal seams with coal seam permeability higher than 1×10^{-15} m^2, the anti-seepage performance of the coal pillar dam should be strictly demonstrated, or anti-seepage reinforcement measures should be taken.

(3) Compared with constant water pressure storage, periodic water pumping and storage operation also help to reduce leakage. Therefore, the water pumping and storage operation should be brought into the water-drainage management of the mining area at the site—to give full play to the water regulation function in the mining area, to effectively reduce the leakage and improve the anti-seepage and stability of the coal pillar dam.

(4) When the coal pillar dam is damaged, permeability increased in the damaged zones; this will increase pore pressure in the lateral range, about three times of the distance

of damaged area. At the same time, due to the existence of damaged zones, water leakage increased significantly (increased by 99% in this case). Therefore, if there is inevitable coal pillar damage in the site, before a formal water storage reservoir, measures such as dam seepage prevention and coal pillar reinforcement are suggested to effectively prevent the occurrence of damaged zones and significantly increase the leakage. The proposed measures and methods also include: spraying anchor on the surface of the coal pillar near the water and supporting with pre-stressed bolt through layers.

7. Conclusions and Recommendations

In this paper, by simulating the leakage of a coal pillar dam of an underground reservoir under different conditions, the following conclusions and understandings are obtained:

(1) Once the overburden fracture zone of the coal mine underground reservoir is filled with water and the reservoir is connected with the upper water system, the water pressure in the reservoir area will be significantly increased, resulting in a substantial increase in leakage. When the water pressure is 100–300 m in water column height, the leakage is 8.19–24.66 times that of the not connected. Therefore, in the site, people should monitor the change in water pressure and, if necessary, pump water to relieve stress in time.

(2) The permeability of the coal pillar dam also influences the leakage significantly. As the permeability decreased from 1×10^{-14} m^2 to 1×10^{-17} m^2, the accumulated water leakage decreased from 4.59×10^7 m^3 to 9.39×10^5 m^3, and the pore pressure also reduced considerably. To build an underground reservoir, coal seams with low permeability and good integrity should be selected as far as possible. It is suggested that the permeability of the coal pillar dam should not be greater than 1×10^{-15}m^2.

(3) The anti-seepage and safety of the coal pillar dam will be significantly improved by periodic water pumping and storage operations. After 30 years of service, the leakage amount decreased to 51.9% of that under constant water pressure storage. Within the range of 0.4 m in the reservoir side of the coal pillar, the pore pressure rapidly reduces by nearly half, dramatically improving the coal pillar's safety performance. Therefore, periodic water pumping and storage operations can not only give full play to the reservoir regulation function but also effectively reduce the leakage and improve the safety performance of coal pillars.

(4) When the coal pillar dam is damaged and its permeability increased, both the pore pressure and leakage amount increased significantly. The existence of the damaged area will bring hidden dangers to the further weakening of the coal pillar dam. At the same time, it will also lead to a substantial increase in leakage (about a 99% increase in this case), which is unfavorable for seepage control. Therefore, before storing water, it can be considered to take measures such as shotcreting the anchor and penetrating the layer anchor to prevent the damage on the reservoir side of the dam body.

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References

1. Gu, D.Z. Water Resource Protection and utilization engineering technology of coal mining in "Energy Golden Triangle" Region. *Coal Eng.* **2014**, *46*, 34–37.
2. Gu, D.Z. Technology Development and Engineering Practice for Protection and Utilization of Water Resources in Coal Mining in Western China. *Front. Eng. Manag.* **2016**, *3*, 59–66. [CrossRef]
3. Liu, J.; Zhao, Y.; Tan, T.; Zhang, L.; Zhu, S.; Xu, F. Evolution and modeling of mine water inflow and hazard characteristics in southern coalfields of China: A case of Meitanba mine. *Int. J. Min. Sci. Technol.* **2022**, *32*, 12. [CrossRef]
4. Xie, X.; Hou, E.; Long, T.; Feng, D.; Hou, P.; Wei, Q.; Li, Y.; Liu, J. Study on Evaluation and Prediction of the degree of Surface Damage caused by Coal Mining. *Front. Earth Sci.* **2022**, *9*, 805248. [CrossRef]
5. Qiao, W.; Li, W.; Li, T.; Chang, J.; Wang, Q. Effects of Coal Mining on Shallow Water Resources in Semiarid Regions: A Case Study in the Shennan Mining Area, Shaanxi, China. *Mine Water Environ.* **2017**, *36*, 104–113. [CrossRef]
6. Hou, E.; Xie, X.; Wang, S.; Long, T.; Shi, Z.; Yang, Z.; Huang, Y.; Xie, Y.; Chen, Z.; Bai, K.; et al. Study on the dynamic law and mechanism of groundwater induced by medium-deep coal mining: A case study from one coal mine. *J. China Coal Soc.* **2022**. Available online: http://kns.cnki.net/kcms/detail/11.2190.TD.20210427.1622.004.html (accessed on 14 June 2022).
7. Wu, H.Q.; Wu, H.F. Demonstration of the influences of coal mining on water resource environment-Taking the dam of Wenyuhe Reservoir as an Example. *SCI-Technol. Inf. Dev. Econ.* **2011**, *2*, 177–179.
8. Gu, D.Z. Water resource and surface ecology protection technology of modern coal mining in China's energy "Golden Triangle". *Strateg. Study CAE* **2013**, *15*, 102–107.
9. Cao, Z.G.; Li, Q.S.; Dong, B.Q. Water resource protection and utilization technology and application of coal mining in Shendong Mining Area. *Coal Eng.* **2014**, *46*, 162–164, 168.
10. Gu, D.Z. Theory framework and technological system of coal mine underground reservoir. *J. China Coal Soc.* **2015**, *40*, 239–246.
11. Gu, D.Z.; Zhang, Y.; Cao, Z.G. Technical progress of water resource protection and utilization by coal mining in China. *Coal Sci. Technol.* **2016**, *1*, 1–7.
12. Gao, R.; Wu, F.; Zou, Q.; Chen, J. Optimal dispatching of wind-PV-mine pumped storage power station: A case study in Lingxin Coal Mine in Ningxia Province, China. *Energy* **2022**, *243*, 123061. [CrossRef]
13. Xie, H.P.; Hou, Z.M.; Gao, F. A new technology of pumped-storage power in underground coal mine: Principles, present situation and future. *J. China Coal Soc.* **2015**, *40*, 965–972.
14. Wang, Q.; Li, W.; Li, T.; Li, X.; Liu, S. Goaf water storage and utilization in arid regions of northwest China: A case study of Shennan coal mine district. *J. Clean. Prod.* **2018**, *202*, 33–44. [CrossRef]
15. Fan, J.Y.; Xie, H.P.; Chen, J.; Jiang, D.; Li, C.; Tiedeu, W.N.; Ambre, J. Preliminary feasibility analysis of a hybrid pumped-hydro energy storage system using abandoned coal mine goafs. *Appl. Energy* **2020**, *258*, 114007. [CrossRef]
16. Kitsikoudis, V.; Archambeau, P.; Dewals, B.; Pujades, E.; Orban, P.; Dassargues, A.; Pirotton, M.; Erpicum, S. Underground Pumped-Storage Hydropower (UPSH) at the Martelange Mine (Belgium): Underground Reservoir Hydraulics. *Energies* **2020**, *13*, 3512. [CrossRef]
17. Bodeux, S.; Pujades, E.; Orban, P.; Dassargues, A. Mines as Lower Reservoir of an UPSH (Underground Pumped Storage Hydroelectricity): Groundwater Impacts and Feasibility. *EGU General Assembly Conference, Vienna, Austria, April 2016*. Available online: http://ui.adsabs.harvard.edu/abs/2016EGUGA..18.3047B/abstract (accessed on 6 April 2022).
18. Menendez, J.; Loredo, J.; Vega, M.G.; Fernández-Oro, J.M. Energy storage in underground coal mines in NW Spain: Assessment of an underground lower water reservoir and preliminary energy balance. *Renew. Energy* **2019**, *134*, 1381–1391. [CrossRef]
19. Menendez, J.; Loredo, J. Numerical modelling of water subsurface reservoirs during the operation phase in underground pumped storage hydropower plants. *E3S Web Conf.* **2020**, *152*, 02001. [CrossRef]
20. Wang, F.; Liang, N.; Li, G. Damage and Failure Evolution Mechanism for Coal Pillar Dams Affected by Water Immersion in Underground Reservoirs. *Geofluids* **2019**, *2019*, 2985691. [CrossRef]
21. 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]
22. Yao, Q.; Yu, L.; Chen, N.; Wang, W.; Xu, Q. Experimental Study on Damage and Failure of Coal-Pillar Dams in Coal Mine Underground Reservoir under Dynamic Load. *Geofluids* **2021**, *2021*, 5623650. [CrossRef]
23. Xin, F.; Xu, H.; Tang, D.; Chen, Y.; Cao, L.; Yuan, Y. Experimental study on the change of reservoir characteristics of different lithotypes of lignite after dehydration and improvement of seepage capacity. *Fuel* **2020**, *277*, 118196. [CrossRef]
24. Xue, Y.; Cao, Z.Z.; Dang, F.N.; Wang, S.H.; He, M.M.; Du, F. Effect of Damage on gas seepage mechanism in coal seam based on a coupled model. *Therm. Sci.* **2019**, *23*, 1323–1328. [CrossRef]
25. Tang, C.; Yao, Q.; Xu, Q.; Shan, C.; Xu, J.; Han, H.; Guo, H. Mechanical failure modes and fractal characteristics of coal samples under repeated drying–saturation conditions. *Nat. Resour. Res.* **2021**, *30*, 4439–4456. [CrossRef]
26. Jia, W.Q.; Liu, Z.H.; Hu, Y.Q.; Chang, Z.X. Research on coupling process of pyrolysis and seepage of coal mass. *Min. Res. Dev.* **2010**, *3*, 40–42.
27. Yin, G.Z.; Zhang, D.M. Transport and gathering of Gas within fractured surrounding rock in deep coal mining. *Sci. Technol. Inf.* **2016**, *6*, 170–173.
28. Shi, X.C.; Meng, Z.P. Coupling effect of mining-induced strain field and permeability coefficient field in surrounding rock of working face. *Coal Geol. Explor.* **2018**, *46*, 143–150.

29. Ma, D.; Duan, H.; Zhang, Q.; Zhang, J.; Li, W.; Zhou, Z.; Liu, W. A Numerical Gas Fracturing Model of Coupled Thermal, Flowing and Mechanical Effects. *Comput. Mater. Contin.* **2020**, *65*, 2123–2141. [CrossRef]
30. Ma, D.; Duan, H.; Zhang, J.; Liu, X.; Li, Z. Numerical Simulation of Water–Silt Inrush Hazard of Fault Rock: A Three-Phase Flow Model. *Rock Mech. Rock Eng.* **2022**, *55*, 5163–5182. [CrossRef]
31. Ma, D.; Duan, H.; Zhang, J. Solid grain migration on hydraulic properties of fault rocks in underground mining tunnel: Radial seepage experiments and verification of permeability prediction. *Tunn. Undergr. Space Technol.* **2022**, *126*, 104525. [CrossRef]
32. Li, J.H. Experimental study of water storage soaking of coal mine underground reservoir to coal pillar dam body strength. *Coal Min. Technol.* **2018**, *23*, 9, 15–17.