

Article

Study of the Catastrophic Process of Water–Sand Inrush in a Deep Buried Stope with Thin Bedrock

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Abstract: Taking the 14,030 panel of Zhaogu No. 2 coal mine as its research object, this paper studies the evolution characteristics of the developing height, propagation track and caving arch shape of water-flowing fractures under the influence of thick alluvium by utilizing a physical experiment, theoretical analysis and field investigation. The results show that the height and limit span of the water-flowing fracture zone experience four stages, which include the initial stage, slow-increasing stage, sudden-increasing stage and stable-increasing stage. With the increase in the mining influence range, the shape of the water-flowing fracture in overburden under the influence of thick alluvium is gradually formed. The water in the thick alluvium and the water in the upper phreatic aquifer of the bedrock penetrate each other to form a concentrated danger zone, and the expansion track of the mining water-flowing fracture connects the hydraulic connection between the upper concentrated danger zone of overburden and the panel of No. 2's first coal seam. A large amount of water mixed with sandstone flows into the fracture surface of the bedrock's broken rock block through the water-flowing fracture, leading to the instability of the load-bearing structure composed of the thick alluvium caving arch and the towering roof beam, which illustrates the whole process of water–sand inrush accidents in thin bedrock stope with deep thick alluvium.

Keywords: alluvium; physical modeling; phreatic aquifer; caving arch; water-flowing fracture



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1. Introduction

As the main energy source in China, coal resources have always been in great demand. According to the data from relevant institutions, China's coal import volume ranked first in the world in 2021, accounting for 323 million tons, which increased 6.6% compared with the previous year. Influenced by external factors such as the Ukraine crisis, the international coal price is running at a high level, and the external pressure on China's energy demands has increased [1–4]. To alleviate China's dependence on international coal inputs and meet the new challenges of the external environment, China has actively adjusted the structure of the coal industry and fully released its advanced coal production capacity. From January to April, 2022, the national coal output was 1.448 billion tons, up by 10.5% [5–7]. Given that the eastern part of China has a relatively developed economy, dense population, great demand for coal energy and a long mining history, it is necessary to explore deep coal resources, and the mining depth of many coal mines has reached kilometers. However, after the mining depth reaches more than 1000 m, the mining difficulty is obviously increased. Under the condition of a deep high-ground stress environment, the surrounding rock is associated with long-term and strong aging stress adjustments after an engineering disturbance, and

the dynamic disturbance and stress wave propagation induced by it have a significant impact on the long-term stability of surrounding rock [8–10].

There are a large number of thick coal seams with deep buried thick alluvium and thin bedrock in the Jiaozuo coalfield in Henan Province and the Juye coalfield in Shandong Province in eastern China. These coal seams are characterized by a deep buried depth (800~1000 m), thick alluvium (700~800 m), thin bedrock (40~100 m), weak cementation, low strength of bedrock and easy disintegration when meeting water [11–14], as shown in Figure 1. There is also a loose phreatic aquifer with unconsolidated sand and gravel as the skeleton at the bottom of the deep buried thick alluvium, which exists directly on top of the thin bedrock [15–20]. When the coal is mined near the loose phreatic aquifer under the action of the thick alluvium, the overburden water-flowing fracture zone is highly developed at the interface between the loose phreatic aquifer and the thin bedrock. Due to the load-transfer function of the loose phreatic aquifer, a large amount of water and sand flow downward along the water-flowing fracture channel of overburden. When water and sand flow into the fracture surface between broken rocks in thin bedrock through a water-flowing fracture, the friction force at the bite point between rocks is reduced, which is unfavorable for the formation of a stable three-hinged-arch balanced structure [21–25]. The sharp increase in the roof subsidence of thin bedrock leads to the overall breaking and structural instability of the thin bedrock under the loose aquifer under certain overburden conditions; this bedrock is prone to support-crushing accidents and water–sand inrush disasters, which pose a serious threat to the safe mining of coal mines [26–29].

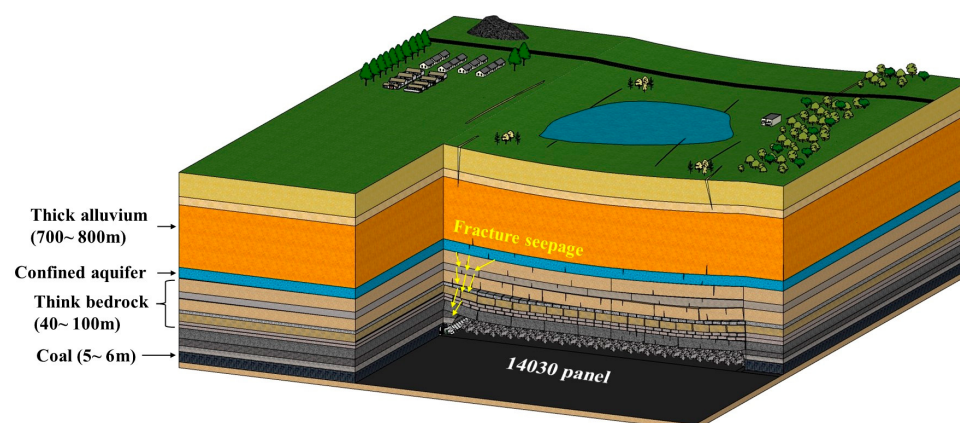


Figure 1. Three-dimensional diagram of strata movement in deep thick coal seam mining with thick alluvium and thin bedrock.

In focusing on the problems mentioned, many scholars have conducted a lot of research. Li et al. [30] studied the fully mechanized top-coal caving mining of an extra-thick coal seam under a water body and found that the development height of the water-flowing fracture zone increases in its shape of step with the periodic breaking of key strata of overburden. When the height of the water-flowing fracture zone develops to a certain level, the soft rock with a certain thickness in the overburden is the key rock stratum to inhibit the water-flowing fracture zone from continuing to develop upwards. Li et al. [31] realized the transformation process of rock mass from continuous medium to discrete medium by using MD-SF constitutive equations and the corresponding FDEM numerical calculation method. The smaller the distance between strata and coal seams, the larger the total width of water-flowing fractures; the total width of fractures in the mining process is 2.26~7.11 times that of the overburden after the overburden movement is stable, indicating that water disasters are more likely to occur during mining. Pang et al. [32] concluded that the greater the dip angle of the coal seam, the closer the area with the most obvious roof separation phenomenon is to the boundary of gob inclined height, and the higher the extension height of the plastic failure zone of overburden. The closer the most developed area of the water-flowing fracture zone is to the boundary of gob inclined to the high place,

the higher the height of the water-flowing fracture zone is. Lai et al. [33] considered that the overburden movement of “three-soft” coal seams under thick alluvium is asymmetric, the maximum subsidence is on the side of the open cut in the center of the gob and the movement range of the alluvium is larger than that of the rock strata at the top of the bedrock, showing a hyperbolic-like shape. Yang et al. [34] believed that the development of a water-flowing fracture zone experiences four stages: initial development, slow increase, sudden increase and stability, and the overburden fracture zone develops upward in the form of separation and exists in the form of a hinge. Xu et al. [35] suggested that the enrichment area of a water-flowing fracture network is mainly concentrated in the front and rear coal walls, and the fracture density near the open cut is greater than that near the stop-mining line. The fracture density curve of the model is skewed “saddle” because the fractured rock in the middle of the gob is compacted and closed under the effect of the overlying load. Huang et al. [36] proposed to judge the subsidence deformation and fracture development degree of rock formations by taking the tensile rate of rock formations as the criterion. When the inflection point of the tensile rate change in the lower hard-rock stratum in each rock stratum group is determined, the fracture development degree of this rock stratum group can be analyzed accurately, which accurately predicts the development height of the water-flowing fracture zone. Xu et al. [37] suggested that the height of the water-flowing fracture zone is affected by the position of the main key strata of overburden. When the main key strata are close to the mining coal seam and less than a certain critical distance, the water-flowing fracture zone will develop to the top of the bedrock. The critical distance between the main key strata and the coal seam mined that has an influence on the height of the water-flowing fracture zone is mainly related to factors such as the mining height of the coal seam, the compaction characteristics of roof breaking and swelling and the fragmentation of the main key strata. The critical distance can be roughly calculated according to the mining height of 7~10 times that of the coal seam.

A physical experiment, theoretical analysis and field investigation were utilized in this study. The main research objective of this study is to master the whole process of the water–sand inrush accident in a deep buried panel with thin bedrock, which also includes development height of water-flowing fractures in the overburden caving arch; analyze the morphological characteristics of the stope roof fracture structure and the relationship with the structural instability of thick alluvium; and construct a coupling model of overburden movement and phreatic flow in a deep buried thin bedrock panel.

2. Engineering Background

This paper takes the 14,030 panel of Zhaogu No. 2 coal mine, which belongs to Jiaozuo coalfield in Henan Province, as the research object. The main coal seam is the No. 2 first coal seam, with an average thickness of 6.5 m. The strata reserved for the bedrock of the coal seam roof are composed of sandstone, sandy mudstone and mudstone of the Lower Shihezi Formation and Shanxi Formation of the Permian; the Neogene strata are above them. The immediate roof is interbedded with mudstone and sandy mudstone, with a thickness of 10 m. The main roof is dominated by sandstone with a thickness of 8 m, and there exists a layer of coarse sandstone with a thickness of 10 m above it, which is the main key stratum. The total thickness of the bedrock above the 14,030 panel is 40~100 m, and the alluvium, which contains several phreatic aquifers, is more than 700 m. The column of the drill hole and the results of drilling at the roof of the bottom drainage roadway are shown in Figure 2 [38].

According to the analysis of the actual exposure of roof drilling, there is gravel in the bottom part of the alluvium in the 14,030 panel, which is wrapped in and consolidated with clay, with more than 20% clay content. The gravel–clay layer overlying the bedrock of the 14,030 panel plays a certain role in water resistance, and it is regarded as an impermeable layer. The thickness of the clay layer exposed by drilling is about 9.96~14 m, and the thickness of the clay layer above the thin bedrock in the 14,030 panel is large, which effectively blocks the hydraulic connection between the water source in the thick alluvium

and the No. 2 first coal seam. In addition, the sandstone aquifer of the thin bedrock roof in the No. 2 first coal seam of the no. 14,030 panel is mainly composed of a Dazhan sandstone aquifer and a coarse sandstone aquifer, with the rock fractures relatively developed. The sandstone aquifer with thin bedrock in the No. 2 first coal seam of the 14,030 panel has a weak water abundance; most of the water enters the mine in the form of water spraying, and the water in the gob is directly replenished after mining, which has little impact on the mining operation.

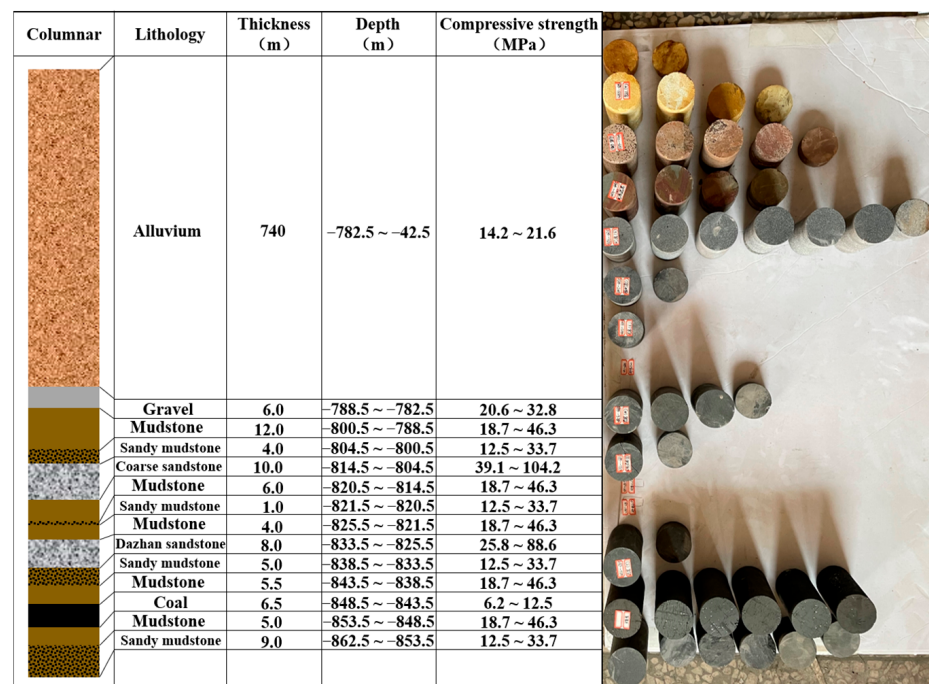


Figure 2. Drilling histogram and rock samples of each layer.

3. Physical Similarity Simulation Experiment

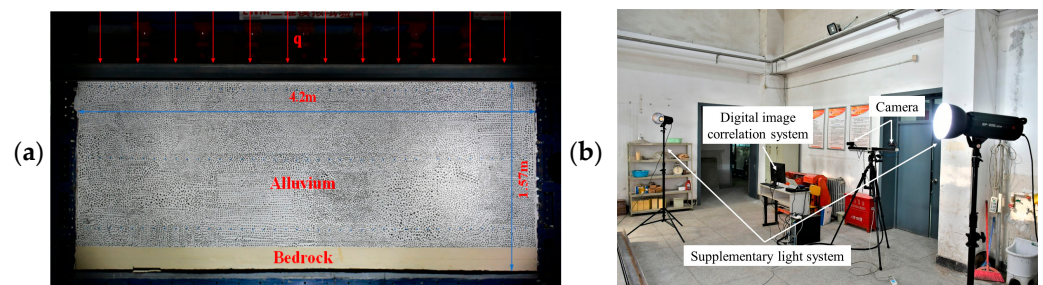
3.1. Experiment Scheme

A physical experiment on deep buried thick coal seam mining with thick alluvium and thin bedrock is carried out. And the characteristics of roof breaking and the evolution law of water-flowing fractures is revealed. The pavement size of the plane-stress model is 4.2 m × 0.25 m × 1.6 m, and the geometric similarity ratio is 1:200, which is paved to the alluvium. Uniform load compensation is applied to the upper boundary of the model to simulate the gravity of the overlying strata without consideration. The model paving materials are mainly river sand, lime, gypsum and water, and a certain proportion of sawdust is mixed in during the paving process of the upper thick alluvium on thin bedrock to realize the similarity of its loose features. The simulation experimental materials and their proportions in each layer are shown in Table 1.

To directly monitor the propagation process of water-flowing fractures on the surface of the plane-stress model under mining disturbance, the thin bedrock is painted light yellow and the thick alluvium is painted milky white, as shown in Figure 3a. The experimental monitoring system mainly includes a DIC (digital image correlation) system and a GoPro high-speed camera system. A DIC system is an optical noncontact three-dimensional deformation measurement system, which is used to measure and analyze the surface morphology, displacement and strain of objects and obtain three-dimensional strain field data. Therefore, the surface of the thick alluvium of the model needs to be randomly sprayed with scattered spots to collect the distribution characteristics of the strain field and the fracture field of overlying strata during coal seam excavation. The arrangement of monitoring equipment is shown in Figure 3b.

Table 1. Experimental materials and their proportions [39].

Layer Number	Lithology	Density/(g/cm ³)	Similarity Materials Compressive Strength/MPa	Similarity Calculation Compressive Strength/MPa	Layering and Thickness/cm	Total Mass per Layer/kg	Ratio Number	Sand Usage per Layer/kg	Ash Consumption per Layer/kg	Amount of Paste Used per Layer/kg	Water Consumption per Layer/kg	
13	Alluvium	1.63	0.023	0.021	60 × 2.00	34.230		Sand:Sawdust:Lime:Gypsum = 10:1:0.2:0.2				4.108
12	Mudstone	1.72	0.137	0.149	4 × 2.25	40.635	855	36.120	2.258	2.258	2.844	
11	Sandy mudstone	1.75	0.185	0.198	1 × 2.00	36.750	846	32.667	1.633	2.450	2.573	
10	Coarse sandstone	1.82	0.265	0.253	2 × 2.50	47.775	746	41.803	2.389	3.583	3.344	
9	Mudstone	1.72	0.137	0.149	2 × 1.50	27.090	855	24.080	1.505	1.505	1.896	
8	Sandy mudstone	1.75	0.185	0.198	1 × 0.50	9.1875	846	8.167	0.408	0.613	0.643	
7	Mudstone	1.72	0.137	0.149	1 × 2.00	36.120	855	32.107	2.007	2.007	2.528	
6	Dazhan sandstone	1.79	0.226	0.211	2 × 2.00	37.380	755	32.708	2.336	2.336	2.617	
5	Sandy mudstone	1.75	0.185	0.198	1 × 2.50	45.938	846	40.833	2.042	3.063	3.216	
4	Mudstone	1.72	0.137	0.149	1 × 2.75	49.665	855	44.147	2.759	2.759	3.477	
3	Coal	1.68	0.108	0.995	1 × 3.25	57.330	955	51.597	2.867	2.867	4.013	
2	Mudstone	1.72	0.137	0.149	1 × 2.50	45.150	855	40.133	2.508	2.508	3.161	
1	Sandy mudstone	1.75	0.185	0.198	1 × 2.00	36.750	846	32.667	1.633	2.450	2.573	

**Figure 3.** Similar simulation physical experimentation: (a) physical object model and (b) monitoring layout.

Since the research method of the physical similarity simulation experiment has some limitations, the model boundary effect has a great influence on the experimental results. Through reasonable boundary conditions and mining process design, the physical similarity simulation experiment can reproduce the phenomenon of strata movement caused by underground coal mining to the greatest extent. Thus, the design width of the boundary coal pillars of the physical similarity simulation experimental model is 0.5 m. The open cut starts from the left boundary of the model at a distance of 0.5 m, with an excavation interval of 0.05 m, and the advance distance stops at the right boundary of the model at a distance of 64 steps in turn, with a total mining of 3.2 m.

3.2. The Development Height of Water-Flowing Fracture Affected by Thick Alluvium

Before the surface of the physical model is deformed, the local strain suddenly increases, resulting in a large number of discontinuous plastic deformations, while most other areas of the model's surface are still in the stage of uniform elastic deformation, which is obviously different. The DIC system captures the speckle image preset on the surface of the model to determine the strain concentration area and obtains the strain concentration distribution of the water-flowing fractures in the overburden caving arch under different advancing distances to predict the development height of the water-flowing fractures, as shown in Figure 4. With the continuous excavation of the mining face, the development height of water-flowing fractures presents an increasing trend. When the panel advances to 25 m, the immediate roof breaks for the first time, the caving height of the bedrock is about 10~12 m and the alluvium is not affected by mining. When the panel advances to 50 m, the sandstone in the main roof breaks for the first time, and the initial weighting occurs. The caving height of the bedrock is about 18~20 m, as the alluvium is still unaffected by mining. As the panel advances to 150 m, with the initial fracture of the coarse sandstone in the key stratum, the bedrock collapses in full thickness for the first time and the caving height of the bedrock reaches 50~62 m; there is a transverse delamination tensile fracture at the interface between the bedrock and the alluvium, and discontinuous microstrain stripes appear in the alluvium. When the panel advances to 250 m, the bedrock collapses periodically, and a number of discontinuous strain concentration stripes on the

caving arch of the thick alluvium extend through each other; the range and degree of strain concentration increase sharply, and the stripes change from discontinuous to continuous, resulting in an increase in the length and width of strain concentration stripes, and the circumferential strain concentration stripes at the boundary of the caving arch change from microdeformation to macrofailure-of-delamination fractures. When the panel advances to 300 m, the caving range of the thick alluvium caving arch increases continuously, and a number of discontinuous microstrain concentration stripes germinate again near the boundary of the new round caving arch. With the continuous excavation of the panel, a plurality of discontinuous strain concentration stripes expand and penetrate each other again, and so on. When the panel advances to 400 m, the range and degree of strain concentration are significantly reduced and tend to be stable due to the crushing and swelling of the caving gangue in the gob. Strain concentration stripes originate at the top of the caving arch in the thick alluvium and continue to spread downward around the boundary of the caving arch along the advancing direction.

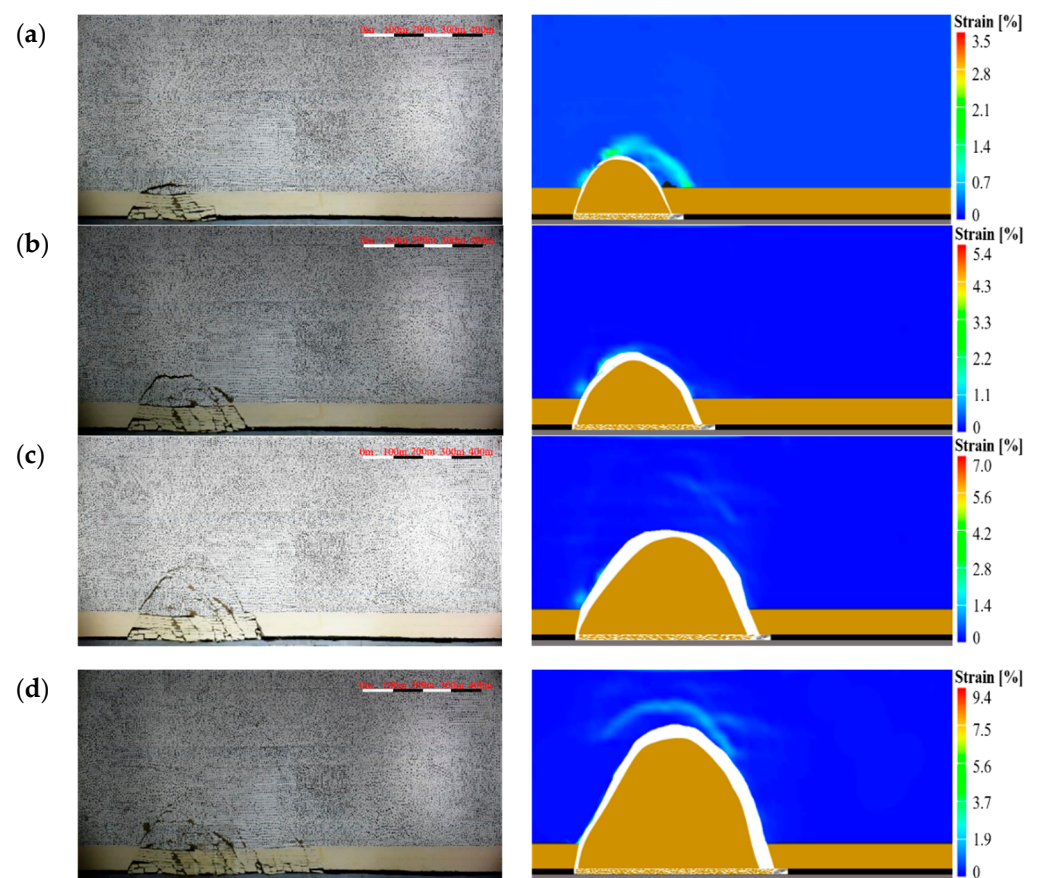


Figure 4. The development height of the water-flowing fracture under different advance distances: (a) advancing 250 m, (b) advancing 300 m, (c) advancing 350 m and (d) advancing 400 m. Note: the color legend means the strain range of overburden deformation.

The development height and ultimate span of water-flowing fractures in the overburden caving arch under different advancing distances are shown in Figure 5. When the advancing distance is 0~100 m, the development of water-flowing fractures is still in the initial stage due to the small influence range of mining, the development height is 0~18 m and the caving arch of the thick alluvium has not yet formed. When the advancing distance is 100~200 m, the development of water-flowing fractures in overburden enters the slow-increasing stage, with a development height of 61~104 m and an ultimate span of the caving arch of the thick alluvium of 30~55 m. When the advancing distance is 200~350 m, due to the sharp increase in the mining influence range, the development of water-flowing

fractures in overburden enters the sudden-increasing stage, with a development height of 162~307 m and an ultimate span of the caving arch of the thick alluvium of 84~122 m. When the advancing distance is 350 m~640 m, the development of water-flowing fractures in overburden enters the stable-increasing stage due to the influence of the crushing and swelling of the coal gangue falling in the gob. Influenced by the height of the top boundary of the model, the model is excavated to 450 m, and the development height and ultimate span of the water-flowing fractures in the overburden caving arch reach a maximum of 377 m and 197 m, respectively. In conclusion, the development height and ultimate span of water-flowing fractures in the caving arch experienced four development stages, which are the initial stage, slow-increasing stage, sudden-increasing stage and stable-increasing stage.

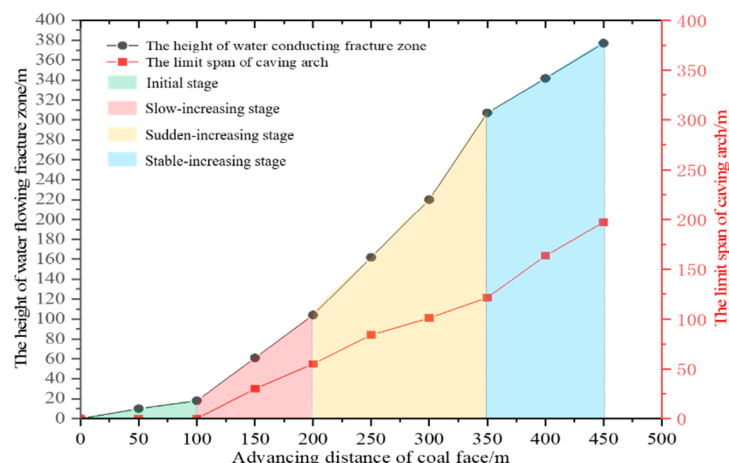


Figure 5. The height and span of the water-flowing fracture zone under different advance distances.

3.3. The Propagation Track of the Water-Flowing Fracture under the Effect of Thick Alluvium

The 16th periodic weighting from the overburden occurs as the panel advances to 450 m. the propagation track of the water-flowing fracture under the effect of thick alluvium is as shown in Figure 6. Given the mining disturbance, the strain concentration fractures in thick alluvium first appear above the top of the caving arch, and the number of fractures continues to increase, which shows a discontinuous trend. With the increase in deformation degree, the strain concentration fractures overlap each other and their shape changes from discontinuous to continuous, with the strain range and degree increasing significantly. The mining fractures appear in the deformation concentration zone where the strain value of fractures is at 5~7%. The monitored mining cracks spread rapidly downward through the phreatic aquifer at the interface between thick alluvium and thin bedrock, resulting in the caving arch of alluvium falling off along the advancing direction and the bedrock breaking in full thickness, finally forming a new composite structure of caving arch and towering rock beam at the arch foot.

Three monitoring points, A, B and C, are set along the expansion path of mining fractures, and the maximum principal strain of the overburden caving arch structure with time under the influence of mining is monitored. The evolution curves of the maximum principal strain of the overburden caving arch monitoring points under the effect of thick alluvium are obtained. At the initial stage of deformation of the caving arch, all monitoring points show a static stage, and no obvious deformation cracking has occurred yet. When the time passes to about 8060 s, the monitoring point A at the top of the thick alluvium caving arch is affected by the tensile stress; a strain concentration fringe with a smaller strain degree and range appears for the first time in the monitoring point area; and the strain range of monitoring point A at this stage is 0–5.37%. When testing time reaches 8560 s, the strain concentration fracture at monitoring point A extends downward to monitoring point B, and the strain curves at monitoring points A and B enter a slow-increasing stage; the strain range of monitoring point A at this stage is 5.37–11.38%. When the time reaches 9060 s, the continuous strain concentration fractures of monitoring points A and B continue

to extend downward to monitoring point C under the inertia, and the strain curves of monitoring points A, B and C all enter a rapid-increasing stage, in which mining fractures generate in the strain concentration fractures of monitoring points A and B; the strain range of monitoring point A at this stage is 11.38–27.47%. When the time reaches 9540 s, the strain degree and range of continuous strain concentration fractures at monitoring points A, B and C suddenly increase and enter a sudden-increasing stage. In the area of monitoring points A and B, the falling body and the mother body fall off; the cracks in the falling arch develop in sequence along the downward direction of $a \rightarrow b \rightarrow c$; the width of the fractures gradually decreases; and the strain range of monitoring point A at this stage is 27.47–73.15%. There exist 4 evolution stages of the caving arch deformation: initial static stage, slow-increasing stage, rapid-increasing stage and sudden-increasing stage.

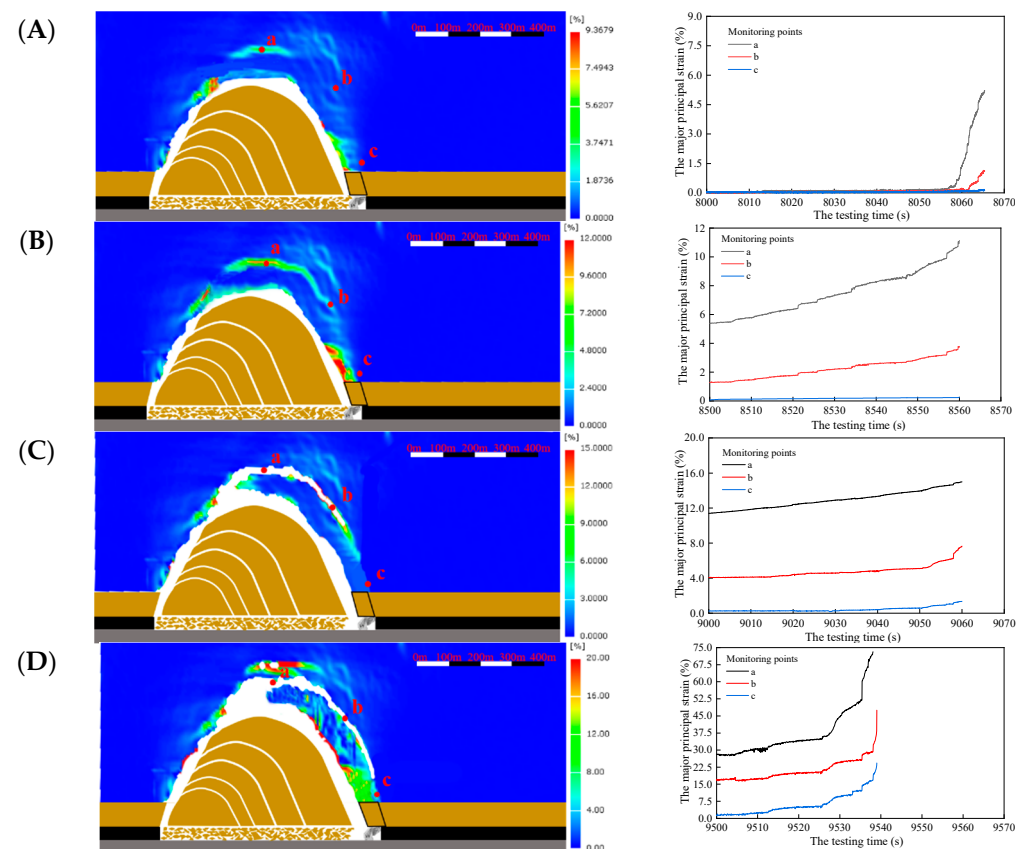


Figure 6. The maximum strain evolution curves of the monitoring point at the caving arch: (A) initial stage, (B) slow-increasing stage, (C) rapid-increasing stage and (D) sudden-increasing stage. Note: the color legend means the strain range of overburden deformation.

3.4. Morphological Evolution Characteristics of the Water-Flowing Fracture in the Multiround Caving Arch

The water-flowing fractures of the multiround caving arch structure in a thick coal seam with deep alluvium and thin bedrock develop downwards in turn, as shown in Figure 7. The entire bedrock collapses when the panel advances to 150 m away from the open cut. At the same time, a horizontal delamination tension crack first appears along the advancing direction at the bottom of the thick alluvium, and then it quickly spreads to the left and right arch feet along the fracture tip, thus forming the first round of the symmetrical caving arch. With the continuous excavation of the panel, a new round of caving arch fractures originates at the top of the first round of the caving arch structure along the advancing direction. Under the effect of inertia, the water-flowing fracture expands rapidly downward and penetrates through the phreatic aquifer at the interface between alluvium and thin bedrock to enter the bedrock, resulting in the rapid release of

internal elastic strain energy. The water-flowing fractures are replenished with energy and continue to expand downward until they penetrate through the whole bedrock, the bedrock is collapsed, the second round of caving arch is formed, and so on. Since all the collapsed rocks in the mined-out area have certain crushing and swelling characteristics, when the fractured bedrock is supported by the crushed and swollen gangue in the gob again, the arch foot on the right side of the caving arch is in the recompressed zone, the deformation and displacement of the overburden decrease sharply and the caving arch stops developing upward. The height and boundary range of its morphological development reach the maximum, the development process of multiround caving arch is ended and the caving fractures in the arch are compacted and bridged again.

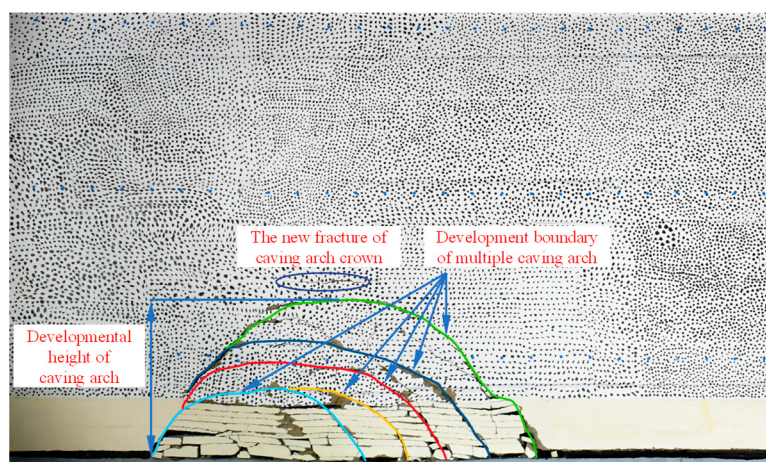


Figure 7. Influence of section shape on horizontal displacement cloud map of surrounding rock of bottom drainage roadway.

According to the morphological evolution characteristics of the caving arch, the formation of the water-flowing fracture channel is highly related to the development of the boundary line of the multiround caving arch. With the excavation of the coal seam and the total collapse of bedrock, the falling blocks in the thick alluvium caving arch generate tensile stress due to the arch's self-weight. When the tensile stress exceeds the tensile strength of the alluvium, mining fractures are formed between the falling blocks and the thick alluvium. Based on the fracture propagation mode and path of the mining separation layer in the thick alluvium, it is inferred that the gravity power of a falling body in the arch is equal to the energy consumption power on the crack propagation path, and the caving boundary equation is obtained, which accurately predicts the load boundary and caving interval of thick alluvium.

4. Discussion

According to the above analysis, it is concluded that the occurrence environment of the overburden in the 14,030 panel of Zhaogu No. 2 coal mine in Jiaozuo coalfield, Henan Province, has the characteristics of large buried depth, thin bedrock and thick alluvium. When the stope with thick alluvium and thin bedrock advances to 100 m, the thin bedrock collapses in full thickness for the first time. Since the sandstone aquifer of bedrock in the 14,030 panel is weak in overall water abundance, it mostly enters the mine in the form of water spraying; thus, it has no significant impact on the panel. With the continuous excavation of the panel, the water-flowing fractures in the thick alluvium of overburden originate at the high position of the top structure of the caving arch in the thick alluvium. Influenced by the additive effect of discontinuous strain concentration fractures under mining disturbance, the water-flowing fractures are transformed from discontinuous strain concentration stripes to continuous ones. The total length and width of the water-flowing fractures increase sharply, and they expand rapidly downward and penetrate through the phreatic aquifer at the interface between alluvium and thin bedrock to enter the bedrock,

resulting in the rapid release of internal elastic strain energy. The bedrock breaks in full thickness and the caving arch of alluvium falls off along the advancing direction, finally forming a new composite structure of caving arch and towering rock beam at the arch foot.

With the increase in the advancing distance and influence range of the panel, the water-flowing fractures on the boundary line of the caving arch in the gob are compacted and bridged again by the influence of the excavation pressure relief effect and the stress rotation effect. The water inside the caving cracks in the thick alluvium is squeezed to the upper position of the overburden on the roof along the development direction of the caving arch boundary fractures. The water in the thick alluvium and the water in the upper phreatic aquifer of bedrock penetrate each other to form a concentrated danger zone, as shown in Figure 8. The gravel–clay layer (impermeable layer) on the bedrock of the 14,030 panel is penetrated by the water-flowing fracture composed of the caving fracture of thick alluvium and the fracture of thin bedrock, which conducts the hydraulic connection between the upper concentration danger zone of overlying strata of the stope roof and the panel of the No. 2 first coal seam. A large amount of water mixed with sandstone flows into the fracture surface of the bedrock's broken rock block through the water-flowing fracture, and it leads to the instability of the load-bearing structure composed of the thick alluvium caving arch and the towering roof beam, which can easily cause support-crushing and water–sand inrush accidents in the thin bedrock stope with deep thick alluvium.

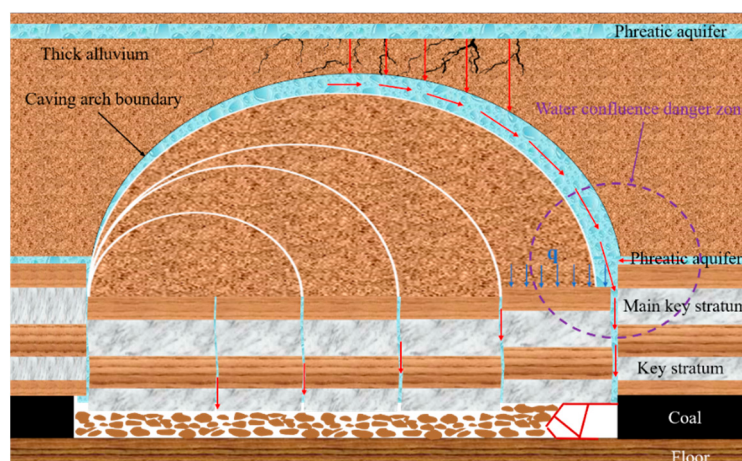


Figure 8. Coupling effect of overburden movement and phreatic flow in thick seam.

To determine the precise location of the overburden phreatic aquifer in the deeply buried stope with thin bedrock, understand the flow pattern of the phreatic aquifer affected by overburden deformation due to mining and verify the accuracy and reliability of the discussion results, we conducted in situ measurements of the apparent resistivity of the overburden using a transient electromagnetic detector before and after the mining of the 14,030 panel. The basic principle of transient electromagnetism suggests a maximum effective detection distance of approximately 100–150 m. The blue low-resistance areas in the transient electromagnetic data represent the phreatic fluid regions, while the red high-resistance areas indicate the solid rock regions. The measured phreatic aquifer fluid regions and the predicted water-flowing fracture results are overlaid and shown in Figure 9.

Before mining, within the effective longitudinal monitoring range of 100 m, most of the overburden rocks in the 14,030 face are in the red high-apparent-resistivity solid rock area. The blue low-apparent-resistivity phreatic fluid area exhibits a discontinuous distribution, primarily located near the interface between alluvium and thin bedrock at 50–60 m and in the boundary region within 100 m of the alluvial layer, which is consistent with the earlier statements in this article. After the working face advances by 200 m into the open cut, the continuous distribution of high apparent resistivity in the rock layer above the mining airspace is disrupted, revealing characteristics of high- and low-resistivity intervals in that direction. There is a downward shift of low-resistivity areas in the longitudinal direction,

indicating that the mining-induced water-flow fractures, spanning the full thickness of the rock during the working face advancement, occur intermittently. Within the longitudinal range of 50~60 m of the overburden strata in the 14,030 panel, the low-resistance phreatic aquifer at the interface between alluvium and thin bedrock converges with the downward movement of the low-resistance layer, leading to water convergence. The phreatic water, along the mining-induced water-flowing fractures, flows towards the working face and the gob, causing a decrease in the apparent resistivity of the bedrock's water seepage zone and an increase in the apparent resistivity loss area of the phreatic aquifer. As a result, the working face becomes highly susceptible to water-sand inrush accidents.

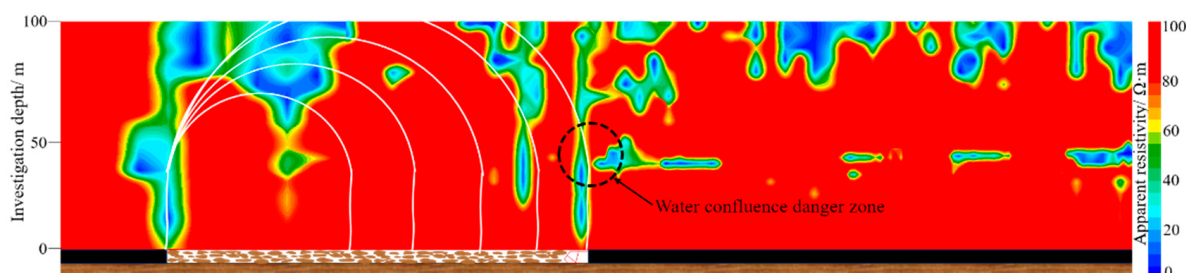


Figure 9. Identification of water and sand flowing path for 14,030 longwall face.

Based on the experimental process and results, we have developed a model to analyze the disaster-causing process of water and sand inrush. However, we acknowledge that the underlying mechanical principles behind the observed phenomenon are deficient. Conducting a quantitative analysis of the model is very important for verifying the accuracy and reliability of the discussion results. In future work, we plan to perform a quantitative analysis of the water and sand inrush mechanism after mining, taking into account the insights gained from our current investigations and the specific characteristics of the deep buried stope with thin bedrock.

5. Conclusions

- (1) With the increase in the advancing distance and influence range of the panel, the deformation of overburden changes from discontinuous strain concentration fractures to continuous strain concentration fractures, and the distribution range and degree of strain concentration stripes on the model surface increase sharply. The height and limited span of the water-flowing fracture zone of the caving arch in overburden experience four development stages: initial stage, slow-increasing stage, sudden-increasing stage and stable-increasing stage.
- (2) The water-flowing fracture of the thick alluvium caving arch originates from a high position at the top of the thick alluvium caving arch. the water-flowing fracture expands sharply downward and penetrates through the phreatic aquifer at the interface between thick alluvium and thin bedrock to enter the bedrock, which leads to the caving arch of thick alluvium falling off and losing stability along the advancing direction. There are four evolution stages, the initial stage, slow-increasing stage, rapid-increasing stage and sudden-increasing stage, during the deformation of the caving arch. Its gravity load is quickly transmitted to the bedrock, and the bedrock breaks in full thickness, finally forming a new composite structure of caving arch and towering rock beam at the arch foot.
- (3) Water-flowing fractures of the multi-round caving arch structure show a developing downward trend in turn, due to the dilatancy of collapsed rocks in the gob; when the degree of dilatancy caused by bedrock breaking and alluvium caving is equivalent to the mining space, the overburden caving arch stops developing upward and reaches the maximum value, and the development of the multi-round caving arch ends.
- (4) The water in the thick alluvium and the water in the upper phreatic aquifer of the bedrock penetrate each other to form a concentrated danger zone. The water-flowing

fracture composed of the thick alluvium caving fracture and the thin bedrock breaking fracture penetrates through the overlying impermeable layer of bedrock and enters the bedrock under inertia. The expansion track of the mining water-flowing fracture connects the hydraulic connection between the upper concentrated danger zone of overburden and the panel of the No. 2 first coal seam. A large amount of water mixed with sandstone flows into the fracture surface of the bedrock's broken rock block through the water-flowing fracture, and it leads to the instability of the load-bearing structure composed of the thick alluvium caving arch and the towering roof beam, which reveals the cause of support-crushing and water-sand inrush accidents in the thin bedrock stope with deep thick alluvium.

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