Failure evolution of collapse column area in deep mine based on numerical calculation and microseismic monitoring

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Abstract. With the depletion of China’s coal resources and the increase in mining depth, high ground stress and high confined water cause frequent accidents. Taking the 12123 working face of Pan’er coal mine in Huainan Coalfield as the background, this study discussed the water disaster caused by the connection of water channels induced by mining disturbance with the collapse column. The catastrophic process of water inrush induced by the collapse column was studied through the numerical simulation of stress field and failure evolution of acoustic emission (AE) interpretation. The grouting method of plugging and reinforcement was introduced, and the effect was evaluated and analyzed. Results showed that the inrush formation of fracture channels was related to the coupling of the physical and mechanical properties of the collapse column and the surrounding rock, mining stress disturbance, and other complex factors. Obvious spatiotemporal effects were observed during structure activation, fracture initiation, fracture expansion, and channel formation of water disaster. The surrounding rock of the collapse column was deformed and split under stress and high water pressure. When the mining face was near the collapse column, the number of AE signals increased sharply from its adjacent top region. After passing through the threatening area, the water channels evolved from the structural bottom to top and produced water gushing. After optimized grouting reinforcement was carried out in the surrounding rock area, microseismic monitoring revealed that the failure depth of the floor in the adjacent area was generally large. The events showed obvious deflection and detour in the collapse column. Few microseismic events occurred on top of the collapse column and its boundary rock, and the spatial distribution of microseismic signals was significantly different from that before grouting, which proved the effectiveness of the grouting method. This study will be conducive to the prevention and control of mine water disasters and promote the wide application of effective grouting technology in mining engineering.

1. Introduction

The hydrogeological conditions of coal mines in China are complex, and floor water inrush has always been the main disaster threatening the safety of coal mining [1-4]. Statistics shows that 619 water disasters occurred in China’s coal mines, including 94 major accidents, from 2000 to 2019 [5]. The floor water inrush disaster of the coalfield in North China bears the brunt, with high frequency and damage degree. The threat of floor water disaster mainly comes from Ordovician limestone water. Ordovician aquifer limestone is characterized by karst development, high pressure, and high water yield. It undergoes multi-stage tectonic movement, which intensifies the hydraulic connection between aquifers.
High-pressure Ordovician limestone water causes large water inflow and high frequency of water inrush in coal mines, leading to poor coal mine safety production [6-8]. Thus, several studies focused on mine water disasters [9-11]. Some mechanical models, such as key stratum of floor water resisting [12,13], vulnerability index method [14,15], and water inrush probability index method [16,17], have been established to prevent such disasters. However, coal mine hydrogeological data are generally incomplete, inaccurate, and complex, which inevitably lead to inaccurate water inrush prediction [21].

Combined with mechanical mechanism, geological conditions, advanced technical means, and monitoring equipment, such as machine learning, microseismic (MS) and grating monitoring, deep studies of water inrush early warning systems considering multiple factors have become the principal method [18-20]. In particular, the combination of numerical simulation and MS monitoring has become one of the technical means to solve key problems [22,23]. The mechanism and control method of water inrush still needs further study.

Approximately 80% of floor water inrush accidents are caused by known large and small faults identified by mine geologists. The aquiclude strata become discontinuous and incomplete. In the study of water inrush mechanism, the aquiclude should be treated as an incomplete rock mass structure [24-26]. All water inrush accidents are caused by the incompleteness of water-resisting rock mass. Only 20% of water inrush accidents have their fracture characteristics not been described or found. Faults and other structures play an important role in the occurrence of water inrush [27]. Structural activation in coal mining is always concealed; thus, understanding the changes in rock mass during structural water conduction activation is important [28,29]. Using the numerical coupling module, Yang found that the water inrush is mainly caused by the activation of the fault layer in mining [28]. Sun analyzed the formation mechanism of water inrush channels in deep fault stope [29]. The floor structure of coal mines is an important factor affecting floor water inrush. Aside from fault, collapse columns are also geological structures that induce major disasters. Karst collapse is a serious geological problem in most coal mines in northern China. With the continuous expansion of collapse columns in coal mines, a semi elliptical stress field is expected to form around the cave; in addition, the local separation layer and fracture zone become potential water channels that induce water inrush easily [30]. Basing from the demonstration of the water inrush model, Li discussed the formation mechanism of water inrush channels of collapse columns [31,32]. When the mining activity is close to the wall or the end of the thick wall barrel, the collapse column has the theory criterion of water inrush disasters. Affected by the collapse column, the stress–strain distribution of floor rocks is uneven [33,34]. Mining activities change the seepage coefficient, and the seepage pressure causes the strain of the surrounding rock of the collapse column. Once the pressure of pressure-bearing water is greater than the minimum principal stress in the key layer, the water seepage softening and fracturing expansion of the pressure-bearing water induce fracture penetration and water inrush channel formation, causing disaster accidents.

The clear exploration of geological structure is the key to solve the threat of well water disasters. After the structure is proved, a reasonable treatment technology must be designed according to the geological characteristics. Therefore, the key to mine water disaster prevention and control technology lies in the calculation theory and method of mine pressure prediction, and the early warning method of precipitation and depressurization. In addition, water pressure mining and plugging grouting control should be combined. Coal mine water disaster prevention and control technology as far as possible to achieve accuracy, transparency, environmental protection, information, intelligent [35]. At present, grouting is a widely used water plugging technology to control large mining area floor water disasters [36,37]. Cement grouting can considerably reduce the permeability of rock mass, thus controlling the movement of groundwater into the roadway [38]. The diffusion mechanism of cement slurry in fractured rock mass is affected by rock mass structure and groundwater flow. The accurate understanding of water flow channel in floor is important for the implementation of effective grouting [39,40]. The implementation of an optimized grouting scheme must be based on actual geological conditions. For stopes with complex structures, such as collapse columns, the evolution of water diversion channels that induce water inrush disasters is important to optimize the grouting scheme, effectively implement grouting, and evaluate grouting effect.

As a real-time monitoring means of rock mass structure damage, MS monitoring has also been widely used in mine disaster prevention. Rocks are damaged under stress, and MS events occur. Arranging
multiple groups of geophones in a certain area and collecting MS data in real time are important. The location and source information of fracture can be determined to obtain the fracture scale and properties [41,42]. MS monitoring can be used to achieve a deep understanding of mining rock mass damage, which also lays an important foundation for the quantitative monitoring and prediction of disasters [43,44]. Jiang FX et al. obtained the activation law of geological structure through real-time monitoring of hidden structures, such as collapse columns, to realize the prediction of water inrush risk [45]. Basing from the waveform data analysis of MS monitoring, Dou LM et al. established a method to evaluate and predict the risk of earthquakes on deep coal mines [46]. With the serious impact of water threat in deep coal mines, the application of MS monitoring in water disaster prevention has been comprehensively studied. Sun YJ et al. used MS monitoring to examine the formation of the water-conducting fracture zone in real time and obtained the spatial position of the water-conducting fracture zone on the floor [47]. Cheng et al. determined the fault activation characteristics and identified the hidden structures in the stope by monitoring the MS response data in mining [48]. To reduce the disadvantages of on-site monitoring, the combination of MS monitoring and numerical simulation can realize mine disaster prediction and early warning [23]. Therefore, MS and numerical technology provides support for the monitoring and early warning of water inrush disasters induced by geological structures.

With the increase in mining depth in the Huainan Coalfield in China, the water disaster is becoming increasingly serious [49,50]. In the 12123 working face of Pan'er coal mine, the hidden collapse column was disturbed during the driving of connecting roadway, and the Ordovician limestone water burst accident occurred at the bottom. In this study, according to the damage evolution mechanism, a numerical model based on the geological conditions of collapse column-induced water inrush in Pan'er coal mine was established in Realistic Failure Process Analysis (RFPA) software, and the temporal and spatial characteristics of water inrush induced by the conduction point of collapse columns during mining were analyzed. The reinforcement area formed by optimized grouting in the collapse column area was explored. The disturbance damage characteristics of the collapse column area during the mining of the working face were studied using MS monitoring.

2. Project overview
Pan'er coal mine is in Huainan, China. At present, coal of group A is mainly mined, which is the lowest minable coal seam in the mining area, as shown in Figure 1. The 12123 working face of the mine is used to mine group A-3 coal seam. The working face is in the West No.2 Mining Area of the first level of the mine. The overlying working faces 14124, 12124, and 12224 have been mined, and the underlying coal of A-1 seam has no mining activity. The upper limit elevation of the working face is -435.6 m, and the lower limit elevation is -508.1 m. The mining strike length of the working face is 1003 m, and the inclined length is 221 m. The dip angle of the coal seam in this block is 3°–22° with an average of 10°. The 12123 working face has 27 faults, of which three are more than or equal to 5 m, two are between 3 and 5 m, and the others are less than 3 m. The main aquifer is composed of Cenozoic loose layer pore aquifer (Group), Permian sandstone fissure aquifer (Group), Carboniferous Taiyuan Group limestone fissure karst aquifer (Group), and Ordovician limestone fissure karst aquifer (Group). Various aquifers with different thicknesses are distributed among each aquifer (Group). The Ordovician water pressure can reach 5 MPa. The average distance between the limestone of Taiyuan Formation and the floor of No.1 coal seam is approximately 16 m. No hydraulic connection exists between the aquifer and upper coal measure strata under normal conditions. A certain degree of hydraulic connection exists with the lower Ordovician limestone aquifer.
During the mining period of the 12223 working face near the working face, two gas drainage rock roadways in the 12123 working face were excavated. The roadway was arranged between the C31–C32 limestone of the C3I group, and the average distance from the 1# coal floor was approximately 17 m. During the excavation period, a sudden water inflow occurred on the floor on May 23, 2017, with the initial water yield of 15 m$^3$/h. Subsequently, the water yield gradually increased to 3024 m$^3$/h, and the instantaneous maximum water inrush reached 14500 m$^3$/h, resulting in partial flooding of the mine. The distribution characteristics of water inrush points and the dynamic changes in water quality, temperature, pressure, and quantity, combined with the comprehensive analysis of limestone water level after water inrush, indicate that Taihui water on the floor is the direct water source of water inrush, and Ordovician limestone water is the supplementary water source. The main water source is Ordovician karst fissure aquifer. The outlet channel is an atypical complex of hidden collapse column and fracture zone, and its upper part is a penetrating core fracture area and influence area. The top of the fracture develops to approximately 25 m below the connecting roadway of the bottom drainage roadway of the 12123 working face, the lower part is the collapse column, and its top boundary develops to the bottom of Taihui, as shown in Figure 1.

### 3. Methodology

#### 3.1 Numerical method

**3.1.1. Governing equations in RFPA.** Rocks are heterogeneous materials composed of homogeneous particles with different properties, and its failure characteristics are affected by its own properties. RFPA software has been widely used in the failure analysis of quasi brittle materials, such as rocks [51-53]. An assumption from the software is that the meso unit of each stratum is homogeneous and isotropic linear elastic-brittle body. In addition, the physical and mechanical properties of each rock meso unit are assumed to obey Weibull distribution to consider the non-uniformity of rock-like materials. Thus, each rock has similar physical and mechanical properties. The homogeneity coefficient $m$ is used to characterize the homogeneity of the material. The larger the $m$ is, the more homogeneous the rock is. The homogeneous index ranging from 1.2 to 5.0 is common for rock materials [54].

$$\sigma(u) = \frac{m}{u_0} \left( \frac{u}{u_0} \right)^{m-1} \exp \left[ \left( \frac{u}{u_0} \right)^m \right],$$  \hspace{1cm} (1)

where $u$ denotes the scale parameter of individual elements, such as strength or the Young’s modulus; $u_0$ is the average element parameter; and $m$ is the rock homogeneity degree, which is defined as the homogeneity index. Rocks can restore their original properties in the elastic stage. Once the stress of the element satisfies the strength criterion (including the maximum tensile stress criterion and Coulomb criterion), damage begins to accumulate. With the development of damage, the elastic modulus decreases gradually. The element can be regarded as a damage element whose residual strength decreases with the increase in deformation. Based on the strain equivalence hypothesis, the elastic
modulus of a damaged element can be expressed as follows:

$$E = (1 - D)E_0,$$

(2)

where $E$ is the changing elastic modulus of damaged element, $D$ is the damage parameter, and $E_0$ is the initial elastic modulus. Damage variables in different mechanical states have different expressions, as shown in Table 1 and Figure 2.

**Table 1** Damage variables under different conditions.

| State                | Expression of damage variable                                      | Conditions                                      |
|----------------------|-------------------------------------------------------------------|-------------------------------------------------|
| Uniaxial tension     | $D = \left\{ \begin{array}{ll} 0 & \varepsilon > \varepsilon_{t0} \\ \frac{\lambda \varepsilon - 0}{\varepsilon} & \varepsilon_{tu} < \varepsilon \leq \varepsilon_{t0} \\ 1 & \varepsilon \leq \varepsilon_{tu} \end{array} \right.$ | $\sigma_3 \leq -\sigma_{t0}$                     |
| Uniaxial compression | $D = \left\{ \begin{array}{ll} 0 & \varepsilon > \varepsilon_{c0} \\ \frac{\lambda \varepsilon - 0}{\varepsilon} & \varepsilon \geq \varepsilon_{c0} \\ 1 & \varepsilon < \varepsilon_{c0} \end{array} \right.$ | $\frac{\sigma_1 - \sigma_3}{1 + \sin \phi} \geq -\sigma_{c0}$ |
| Triaxial shear states| $D = \left\{ \begin{array}{ll} 0 & \varepsilon_{1} > \varepsilon_{c0} \\ \frac{\lambda \varepsilon - 0}{\varepsilon_{1}} & \varepsilon_{1} \leq \varepsilon_{c0} \end{array} \right.$ | $\sigma_{c0} = E_0 \varepsilon_{c0} - \frac{1 + \sin \phi}{1 - \sin \phi} \sigma_3 + \nu (\sigma_1 + \sigma_2)$ |

where $\lambda$ is the coefficient of residual strength, $\varepsilon_{t0}$ is the limit strain, $\varepsilon_{tu}$ is the ultimate tensile strain, $\varepsilon_{c0}$ is the limit compressive strain, $\sigma_1$ and $\sigma_3$ are the principal stresses, $\phi$ is the friction angle, $f_0$ is the uniaxial compressive strength, $\nu$ is Poisson's ratio, and $\varepsilon_{1}$ is the maximum compressive principal strain.

**Figure 2.** Elastic-brittle damage constitutive law and damage variable

### 3.1.2. Calculation parameters

When using any numerical calculation software to simulate the in situ geological model, the input parameters are very important because they determine the reliability of the simulation results. When RFPA is used for simulation analysis, the rock mass medium of excavation engineering is generalized as a non-linear space body composed of layers with excavation holes. Each layer has similar physical and mechanical properties and is heterogeneous and isotropic. In general, the micromechanical parameters used in numerical simulation are determined by the physical, mechanical parameters and homogeneity of actual rock mass, and the parameters used in numerical simulation analysis are selected. In view of the practical problems, a numerical sample is first established, whose geometric size is in the same order of magnitude and close to the actual engineering problem to be studied. When selecting the calculation parameters, the numerical sample size is 100 m $\times$ 50 m and divided into $200 \times 100 = 20000$ finite element meshes. Then, a homogeneity coefficient is selected. In this paper, the homogeneity coefficient $m$ = 2 is selected. According to the fitting formula, the input elastic modulus and rock strength are preliminarily selected.

$$\frac{\sigma_{cs}}{\sigma_{c0}} = 0.2602 \ln m + 0.0233$$

$$\frac{E_{cs}}{E_{c0}} = 0.1412 \ln m + 0.6476$$

(3)

where $E_{c0}$ and $\sigma_{c0}$ are the mean values of elastic modulus and strength when Weibull distribution is assigned (input value for calculation), respectively. $E_{cs}$ and $\sigma_{cs}$ are the macroscopic elastic modulus and strength (measured value) of the numerical sample, respectively.

Taking the parameter selection of mudstone as an example, the compressive strength of rock mass is
6 MPa and the elastic modulus is 2.1 GPa. According to Formula (1), the selected input values are as follows: compressive strength of 29.5 MPa and elastic modulus of 2.8 GPa. Finally, the numerical simulation of uniaxial compression is carried out for the established numerical sample, and the peak strength of the sample is observed. Due to the good repeatability and operability of the numerical calculation, the selected initial value of calculation input can be adjusted in a small range. The macro compressive strength of the obtained sample should be consistent with the actual engineering rock mass strength, as shown in Figure 3. The peak strength of the sample has reached 5.96 MPa, which is close to the macro compressive strength of the mudstone.

![Figure 3. Calculated strength curve of typical rock](image)

The final parameters of each stratum from the calculation are shown in Table 2. RFPA is used to design a 2D plane strain calculation model with a size of 200 m × 120 m and 96000 elements, as shown in Figure 4. The top of the collapse column is approximately 25 m away from the mining floor, the bottom of the collapse column relates to the aquifer, and the water pressure of the aquifer is 5 MPa. The higher confined head pressure is transferred to the underlying aquifer of the coal seam through the boundary. The rock mass only bears self-weight stress and water pressure. The left and right boundaries of the model are constrained horizontally and can be moved vertically. The lower boundary is fixed, and the bottom and top are set as impermeable boundaries. The upper boundary is applied with approximately 10 MPa uniform vertical stress to simulate the gravity of overlying strata. The water inrush of the bottom collapse column during excavation is simulated by step excavation. The calculation model is excavated 50 m to the left of the rock layer, and the simulated excavation speed is 5 m/day for each calculation step until the collapse column is exposed.

| Rock    | Thickness / m | Elastic Modulus / GPa | Compressive strength / MPa | Poisson's ratio | Friction angle/° | Density kg/m³ | Permeability | Pore pressure coefficient | Ratio of compressive to tensile |
|---------|---------------|-----------------------|----------------------------|-----------------|------------------|---------------|--------------|--------------------------|-------------------------------|
| Overburden | 10            | 4.02                  | 10                         | 0.25            | 30               | 2900          | 0.1          | 0.1                      | 10                            |
| Sandstone | 42            | 8.05                  | 10                         | 0.2             | 37               | 2500          | 0.1          | 0.1                      | 10                            |
| Coal    | 3             | 2                     | 5                          | 0.3             | 30               | 2100          | 0.1          | 0.01                     | 15                            |
| Limestone | 15            | 13.42                 | 12                         | 0.2             | 40               | 2500          | 100          | 0.99                     | 10                            |
| Mudstone | 50            | 2.82                  | 6                          | 0.28            | 35               | 540           | 0.1          | 0.01                     | 15                            |
3.2 Rock failure evolvement with AE and MS

The failure of rocks under load induces acoustic emission (AE), and the whole process of rock failure under external force is always consistent with the trend of AE parameters [55]. AE signals obtained by equipment can characterize the whole process of rock failure and precursor information of complete rock instability. As shown in Figure 5, several MS events occur in macro failure after the peak strength of the rock, and each stage has obvious differences, especially before and after the complete failure. For the typical total stress–strain curve of rocks, in the OA stage, the micro cracks in the rock are closed under pressure, and the rock structure is compacted. In this stage, very few AE events generally do not occur or occur. AB is the stage from elastic deformation to stable development of microcracks, in which a small amount of AE signals occurs. The principal AE sources in these two stages are the closure, compaction, friction, and sliding of primary fractures. BC is the stage of rock transformation from elastic stage to plastic deformation. The cracks in rocks produce new cracks with the stress loading, and then AE signals gradually show clustering characteristics. After stage C, the rock interior is greatly damaged, and many AE signals are rapidly generated. The main AE sources in these two stages are the generation of new cracks and the sliding fracture of rock structural plane. Capturing the difference and omen of fracture signals before and after rock failure can provide strong support for the study of dynamic fracture of large rock mass.
earthquakes in essence. Many MS theoretical supports are derived from the results of indoor AE experiments. Therefore, the results of AE can provide some support for the feasibility of MS monitoring in the field. In other words, the AE and MS signals induced by rock mass fracture can be used to identify rock mass instability at different scales and frequencies.

Figure 6. Frequency distribution of AE, MS, and earthquakes

4. Evolution of water inrush from collapse column

4.1 Evolution of stress
The excavation calculation of the model was carried out, and the stress evolution state of the stope with the collapse column during mining is shown in Figure 7.

Figure 7. Stress evolution during excavation

a. The collapse column (a) and surrounding rock are in a relatively stable state without excavation. However, a certain stress concentration exists at the boundary of the collapse column. This phenomenon can be ascribed to the significant difference in mechanical properties between the collapse column and the surrounding rock, leading to the uneven distribution of original stress field. However, in the original state, all types of surrounding rock are in a relative equilibrium state.

b. After advancing a certain distance from the mining face (b), only a small range of stress concentration exists at the end position because of the small mining distance. In addition, a small stress occurs at the bottom of the top.

c. As the working face continues to advance (c), the stress concentration range increases significantly. In addition, the distance between the end and the collapse column is further reduced, which leads to the stress concentration area and the disturbance of the bottom collapse column, and changes the initial stress distribution of the surrounding rock of the collapse column.

d. After the mining face reaches the top of the collapse column, the stress concentration area expands. However, at this time, the collapse column is located in the intersection area of the concentration area,
and the surrounding rock begins to accumulate damage because of interface stress.

e. After the working face pushes through the collapse column, the collapse column is at the junction of the floor high stress and in situ stress distribution. Due to the continuous interference of mining stress, the surrounding rock and roof and floor of the collapse column are destroyed. At this time, the physical and mechanical properties of the working face degenerate and the mechanical properties disappear, that is, the completely damaged element.

f. Finally, the working face continues mining, and the stress concentration in the longitudinal range is not expanding. Currently, the collapse column is completely in the lower part of the goaf. Several vanishing units of typical mechanical parameters appear, and cracks form on the floor of the working face and goaf.

In the stress evolution of the floor and collapse column with mining, the distribution of mining stress is significantly related to the advance of mining face. Stress has typical space–time characteristics. When the working face advances to the vicinity of the collapse column, the mechanical properties of the element begin to degenerate completely. The best state of shear failure is when the boundary line of the compression and expansion zones of the collapse column is coincident. At this time, this phenomenon is most likely to cause water inrush due to damage and aggregation.

4.2 Evolution of water inrush disaster from AE events

According to the relationship between AE signal and rock fracture, the AE evolution module is introduced into RFPA. The distribution characteristics of AE (MS) during stress evolution are shown in Figure 8. In the initial state, the mechanical strength and performance of the collapse column are weak because the column itself is a block filled with clay. Thus, its interior contains AE signals and initial damage. When the driving distance is small at the beginning of the mining face, the collapse column is still damaged only under the initial condition, and no new AE signal appears (a–b). With the continuous advance of the working face and disturbed by mining stress, new AE signals appear on the floor near the coal seam, the top of the collapse column, and the boundary position. When the working face advances to the upper position of the collapse column, the AE signal increases significantly. The AE events in this stage are mainly distributed in the surrounding rock between the F of the working face and the top of the collapse column. This phenomenon decreases when pushing a certain distance. However, the failure elements of rock form and scatter on the floor. Finally, with continuous further mining, the surrounding rock fracture conduction in the collapse column boundary area is completely formed, and the AE signal on the floor goaf between the top and the coal seam increases significantly. The AE appears obvious bifurcation, and the fracture channel is completely formed. From the left interface of the collapse column to the end of the working face, the bifurcation develops to the inner side of the goaf, and a new damage fracture occurs at the intersection.

The derivation of AE signals is consistent with the response of rock mechanical properties under stress distribution. When the working face is advanced to the top of the collapse column, cracks form from the top of the collapse column interface to the coal seam from bottom to top. After the collapse column is pushed forward in the working face, a large range of fracture appears. Furthermore, the evolution of rock mechanics and seepage fields is combined, as shown in Figure 9. The non-penetrating primary defects around the collapse column and the permeability of the column fracture filling body are significantly improved. Then, the induced fracture water is accelerated. It causes scouring and expansion on the fracture wall, expansion of the original fracture, the initiation of a new fracture, the change in fracture width, and the mutual connection of fractures. Finally, it affects the overall permeability and integrity of the floor water-resisting rock mass. The seepage of high-pressure water is transformed into fracture flow and finally flows into the stope along the water inrush channel from the aquifer.
Figure 8. AE events during excavation

The activation of the collapse column to water inrush is a gradual process with a significant space–time effect and a clear relationship with the mining position, collapse column interface, and its own performance. The whole process includes wedge splitting of high-pressure water, crack opening, dissolution of filling material in the column, crack penetration, and final hydrodynamic contact erosion. The ultimate activation of the collapse column is the macroscopic manifestation of the deterioration of its physical and mechanical properties with time and the accumulation of meso damage of the medium under long-term environmental impact and load. The significant difference between the collapse column and the surrounding rock results in great damage and fracture. At the same time, the seepage stress exerts a splitting effect on the rock in the cracks generated by the collapse column interface, which connects with the upper cracks, resulting in the complete formation of water channels. According to the water gushing characteristics of the collapse column, the treatment project of the collapse column must be based on existing space–time characteristics. The activation of the collapse column must be controlled from bottom to top to reinforce the interface between the collapse column and the surrounding rock. Through grouting, the high strength range of the collapse column “above the waist” should be expanded to avoid shear failure at the interface due to the loss of coordination between the collapse column and the surrounding rock, and to prevent crack expansion under hydraulic scouring.

Figure 9. Distribution of seepage field

5. Rock failure of grouted zone in the collapse column

5.1 Grouting method
The project adopts horizontal directional drilling on the ground to explore the vertical water-conducting
structure in the five-ash and six-ash strata of group A coal floor. Simulation results (Figures. 8 and 9) show that cracks are preferentially generated from the interior and interface of the collapse column, and the strength of this part must be strengthened to prevent damage. The high-pressure grouting technology is used to cement the exposed vertical water flowing fractures to block the channels and prevent the deep limestone water from entering the working face.

The whole grouting process lasts for 90 days. Five groups of grouting holes are completed, including four main holes and 31 branch holes. The final hole grouting pressure is 8.0–10.2 MPa. The grouted area is 422,480 m², the drilling and grouting construction of each hole have reached the design end standard, and the established treatment target has been completed. Grouting is conducted under the conditions of a limestone karst fissure and fracture zone exposed by drilling, and the fracture is sealed by continuous high-pressure grouting in sections and sequence to remodel the limestone aquifer and block the channel of water flowing into the mine. This process eliminates the water inrush to the greatest extent, guaranteeing the safety production of the mine. The main grouting material is a PC32.5 composite Portland cement. When large leakage fissures or caves are encountered in limestone, cement slurry with a specific cement water ratio of 1.2–1.6 is injected with a displacement of 390 L/min to rapidly fill the fractures or caves. When the drill flushing fluid, leakage is small and the drilling hole grouting is completed. The high-pressure grouting spreads the slurry to the pores and small fissures in the rock layer to increase the diffusion distance and fill the fine fissures, as shown in Figure 10.

**Figure 10.** Grouting method in collapse column and floor

In floor grouting transformation, the comprehensive analysis of drilling trajectory of each directional horizontal branch hole, geological logging, water pressure test, and grouting single hole end standard indicates that the effect of the surface area advanced exploration and treatment project is good. Grouting can cut off the hydraulic connection between group A coal and Ordovician limestone aquifer in the treatment area, and the exploration and treatment of fracture water channels are completed. The Ordovician limestone water inrush coefficient of the floor of the 12223 working face (the remaining section) after transformation becomes 0.055 MPa/m. The Ordovician limestone water inrush coefficient of the 12123 working face floor becomes 0.051 MPa/m. The water inrush coefficient of the two working faces is less than 0.1 MPa/m of the normal block. Thus, the normal mining on the Ordovician limestone layer can be carried out.

5.2 Microseismic events in the rock mass

5.2.1. Microseismic monitoring system. Two gas drainage roadways on the floor and two roadways in the coal seam can be found in the roadway system of the 12123 working face. Considering the monitoring effect of the floor, the ESG MS sensor is installed in the floor roadway with a certain...
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12

elevation. The ESG MS monitoring system mainly includes three parts: a sensor, a Paladin underground digital signal acquisition system, and a Hyperion ground digital signal processing system. The MS monitoring system can continuously monitor several MS events in real time and 24 h. It can also obtain many source parameters, such as time–space coordinates, errors, magnitude, and energy. The collected data are filtered to provide the complete waveform and spectrum analysis chart of the user's source information. The types of MS events can be identified automatically. Noise events are eliminated by filtering, threshold setting, and bandwidth detection.

A total of 18 monitoring points are arranged in the working face, and 9 sensors are arranged in each roadway, as shown in Figure 10. The measuring points of the upper and lower roadways are from 1 to 9, and the sensors of the lower roadway are from 10 to 18. The sensors in each roadway are arranged at an interval of 100–115 m, realizing the spatial staggered arrangement. Effective high-precision monitoring area can be realized during the mining of the working face. The main faults and collapse columns in the working face are included in the area, which can provide strong guidance in the face mining. The 3D diagram of the monitoring range is shown in Figure 11, and the cross distribution can realize the effective monitoring of the working face.

![Figure 11. Microseismic monitoring system](image)

5.2.2. Failure analysis based on MS monitoring. The 12123 working face began to “cut” the calibrated area of collapse column in floor from the mining line around March 5. The collapse column area completely enters the influence range of advanced concentrated stress of the working face. On March 27, the mining line began to cross the collapse column area, and the collapse column began to be in the range of goaf, as shown in Figure 12. The top of the collapse column completely enters the goaf. According to the failure conditions of the rock and the stress distribution characteristics of the stope, the collapse column is in the floor “expansion zone” during this period. In particular, the collapse column transition is in the boundary area of the “compression area” and the “expansion area” due to continuous mining in the working face, leading to typical failure.

![Figure 12. 12123 working face](image)
Figure 13. Variation characteristics of microseismic events

Approximately 2350 MS events occurred from March 1 to March 26. According to the contour line of coal seam floor and plane coordinates of MS events, the MS events of coal seam floor were further analyzed. Exactly 530 effective MS events are recorded on the floor, accounting for 22.5% of the total events. The maximum depth of the floor is approximately 86.5 m (3.13 days). The variation trend of MS events in the single-day floor is shown in Figure 13. After entering the collapse column, the MS events in the floor show an obvious growth trend. Since March 11, the number of MS events on the floor has increased significantly (the average is approximately 25). A large increase occurred at around March 18, after which the increase was in a large range (mean 32). The number of MS events then decreased to the earlier period on March 24.

Figure 14. Spatial side view of microseismic events during mining

Figure 15. Spatial front view of microseismic events during mining
The MS events during mining are further analyzed on the basis of the results of MS monitoring and mining conditions. The spatial distribution of MS events on the floor when they affect the collapse column and its fracture zone is shown in Figure 13. The corresponding dates in Figure 13 (a, b, c, d, e, f) are 3.1–3.2, 3.6–3.7, 3.11–3.12, 3.16–3.17, 3.21–3.22, and 3.25–3.26, respectively. The spatial relationship with the working face is shown in Figures 14 and 15. MS events mainly occur in the surrounding rock between the mining face and the top of the collapse column in the initial wave stage. With continuous mining, the location of MS events shift to the left. The distribution depth of MS events reaches the maximum when the mining face advances to the top of the collapse column. Most of the MS events are still distributed in the surrounding rock at the top of the collapse column. Compared with the base slab without grouting, no MS event is observed at the collapse column and its interface. After grouting, the interface of the collapse column is effectively reinforced, and the MS events basically occur around the collapse column. The main reason for this phenomenon is that grouting reinforces the rock strata in the collapse column and its waist. However, the mechanical properties of the surrounding rock at the top and that at the junction of the top and waist are different because grouting is not carried out in the rock layer in the top horizontal position, the MS events mainly occur at this position.

Moreover, all the MS events in the stage are imaged in the 3D map. MS events have deflection/detour phenomenon in the grouting reinforcement area of the collapse column, which further proves the effectiveness of the grouting method. However, some deep MS events occur in the area near the collapse column, the floor failure event is maintained in a certain range, and no deep fractures are observed, as shown in Figure 16. In the mining line and collapse column area of the working face, a certain deepening of floor failure occurs. Nearing the collapse column (such as the grouting interface), a crisscross of the upper and lower event radii occurs, forming a new fracture.

Figure 16. Microseismic events from the front and side views in the whole stage

Comparison of the numerical results without grouting (Figure 8) and the fracture signals shown by MS monitoring after grouting (Figures 14 to 16) shows that under non-grouting, AE signals first occur in the collapse column, which causes abnormal stress distribution of the surrounding rock. Then, under the mining stress, the coal floor produces fracture and AE signals, and gradually penetrates into a joint with the interface of the collapse column. From the interface and top of the collapse column, a connecting fracture is formed upward, resulting in water inrush accidents. In the numerical model, the connection between the interface and the rock stratum fracture at the top becomes the key factor to
induce water inrush. However, the slurry strengthens the collapse column and its interface after completed grouting. Thus, no more MS events (micro fractures) are observed at this location. In the top rock stratum, damage still occurs because of the influence of mining. The failure modes of the two are similar: when the working face is close to the collapse column, the MS/AE event appears in the rock stratum at the top of the collapse column (Figures 14 and 15 (b → c) and Figure 8 (d)). When mining coal after the collapse column, the MS event completely covers the collapse column and expands to the deep (Figures 14 and 15 (e → f) and Figure 8 (f)). However, some differences are found. Compared with the case without grouting (Figure 8 (f)), no MS/AE event occurs at the collapse column and its interface, and the overall distribution shows a “deflection” phenomenon (Figure 16). Therefore, the grouting vein improves the strength of the interface, blocks the downward derivation of mining failure, and prevents the further penetration and development of deep splitting fractures.

6. Conclusion
Aiming at the induced collapse column in deep coal mines, this study constructed a numerical calculation model with the floor collapse column of the 12123 working face in Pan'er coal mine of Huainan Coalfield in China as the background to analyze the activation process to form water channels. The characteristics of induced water inrush, stress evolution, AE signal, and seepage field distribution were analyzed. The effect of the optimized grouting method was evaluated using the MS monitoring system. The main conclusions are as follows:

The formation of water channels has relative spatial characteristics with the mining position of working face, and the water inrush process has a time–space effect. The spatiotemporal correction of water inrush channels in numerical simulation was realized through the analysis of stress field, damage field, and floor flow. After advancing a certain distance, the stress field of the surrounding rock in the collapse column would interfere with mining stress. When the working face is close to the top of the collapse column, the collapse column is in the cross area of concentrated stress. At the interface of the collapse column, AE signals re generated first, and the mechanical properties of the elements in the region start to weaken. The collapse column and floor under the goaf are disturbed continuously in the working face, resulting in some failure elements (mechanical properties disappear). The fracture zone between the interface and the surrounding rock appears after coal mining. The AE signals gather at the interface of the collapse column and spread laterally to both sides.

The path of water inrush is controlled by the occurrence factors, physical and mechanical properties, and external stress disturbance of collapse column. The evolution of rock mass from the water-resisting layer to the conducting channels is following with that fracture initiation, propagation, and water pressure tracking transfer are driven by water pressure. Collapse column activation is a macroscopic manifestation of the deterioration of physical and mechanical properties with time and accumulation of meso damage of medium under long-term environmental impact and load. The collapse column is prone to shear deformation and damage in the incongruous strain. The splitting effect of high-pressure seepage water makes the newly initiated crack on the floor open gradually.

The time characteristics of MS events in the surrounding rock of the collapse column with optimized grouting are basically consistent with those without grouting. MS events occur in the surrounding rock when the collapse column is disturbed in the working face. Many MS events occur after reaching the top of the structure. However, the spatial characteristics have considerably changed. MS events show obvious deflection in the calibration area of the collapse column. No linear cluster events occur at the interface. The floor failure event is maintained in a certain range, and no deep fractures occur, which further verify the effectiveness of the grouting method.

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