

## Article

# Analysis of Water Inrush Disaster Mechanism of Inter-Layer Rocks between Close Coal Seams under the Influence of Mining

Jie Zhang <sup>1,2</sup>, Jianjun Wu <sup>1,2,\*</sup>, Tao Yang <sup>1,2</sup> , Sen Yang <sup>1,2</sup> , Yifeng He <sup>1</sup> and Shoushi Gao <sup>1</sup>

<sup>1</sup> School of Energy Engineering, Xi'an University of Science and Technology, Xi'an 710054, China; zhangjie655@xust.edu.cn (J.Z.); yangtao@xust.edu.cn (T.Y.); yangsen2009@outlook.com (S.Y.); heyifeng274015@stu.xust.edu.cn (Y.H.); 1650150717@stu.xust.edu.cn (S.G.)

<sup>2</sup> Key Laboratory for Mining and Disaster Prevention in the West of the Ministry of Education, Xi'an 710054, China

\* Correspondence: wujianjun@stu.xust.edu.cn

**Abstract:** With the gradual increase in the mining depth of coal resources, the destruction of the rock structure of the inter-layered rock of the near coal seam under the influence of mining has led to the frequent occurrence of water-inrush disasters in mines, which seriously affects the safety of mine production and the safety of the people in the underground. Therefore, it is important to study the mechanism of the water inrush of the rock between the coal seams under the influence of mining to control the occurrence of water inrush disasters and protect the loss of groundwater resources. This paper takes the Hanjiawan coal mine with typical stratigraphic characteristics as the background for research and studies the structural characteristics of interlayer rock breakage and the solid–liquid coupling inrush water disaster mechanism during the mining of 2<sup>−2</sup> and 3<sup>−1</sup> coals. The study shows that according to the damage degree and destruction depth of the inter-layered rock caused by the mining of the upper and lower coal seams, combined with the slip line theory and the “three bands” collapse theory, the inter-layered rock is classified into a completely fractured inter-layer, a fractured–broken stacked inter-layer, and a fractured–broken–fractured combined inter-layered rock using  $L \leq h_m + H_{k2}'$ ,  $L > h_m + H_{k2}'$ , and  $L \geq h_m + H_{l2}'$  as the discriminating criteria. Combined with the structural classification of inter-layer rock and the discriminating criteria, we used similar simulation experiments and on-site research to analyze the evolution law and distribution characteristics of four types of inter-layer rock water-inrush fractures in different mines and put forward the classification of inter-layer rock water-inrush channels based on the width, length, and penetration of the fractures. Based on the characteristics of the water-inrush channel of inter-layer rock, we constructed the network-boundary inrush water calculation model of inter-layered rock and network-attach-boundary inrush water calculation model, solved the water movement of the water-inrush channel in the model by transforming the flat flow state, fracture to flow state, and pore-fracture flow state, and finally revealed the mechanism of the disaster by which water-inrush of inter-layer rock was induced. Finally, we revealed its mechanism of inducing the inter-layer rock inrush water disaster. Our research enriches the theory and research ideas of the water-inrush disaster, provides theoretical support and a basis for the control of water-inrush disasters in similar conditions, and ensures the safe production of mines.

**Keywords:** close distance coal seam; inter-layered rock; structural classification; inrush water disaster mechanism; flow-solid coupling model



**Citation:** Zhang, J.; Wu, J.; Yang, T.; Yang, S.; He, Y.; Gao, S. Analysis of Water Inrush Disaster Mechanism of Inter-Layer Rocks between Close Coal Seams under the Influence of Mining. *Appl. Sci.* **2023**, *13*, 9043. <https://doi.org/10.3390/app13159043>

Academic Editor: Andrea L. Rizzo

Received: 9 July 2023

Revised: 31 July 2023

Accepted: 4 August 2023

Published: 7 August 2023



**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

Mine watered inrush has always been one of the most serious disasters in the production process of coal mines in China and abroad. Long-wall comprehensive mechanized mining has a severe impact on the failure of the lower rock mass. The complex geological conditions of the close-distance coal seam make the evolution mechanism of the water inrush in the interlayer rock more complex and difficult to measure [1]. When groundwater

and gob water enter the lower coal seam working face and gob through the water inrush channel, it is easy to cause mine water inrush accidents and serious loss of groundwater resources. In this process, how the groundwater and gob waters flow through the inter-layer rocks mass under the influence of mining, what kind of theory the movement process follows and what kind of fluid–solid coupling model is in line with are unknown. Therefore, it is extremely important to the establishment, analysis, and water inrush mechanism research of the water inrush model of the lower rock mass affected by mining. Effective prediction and the prediction method of the water inrush of the inter-layer rocks mass and control of the water inrush disaster are also of great significance.

In recent years, water inrush accidents have occurred frequently in eastern and western coal mines in China, causing serious economic losses and casualties [2–4]. The water inrush sources and water inrush channel of inter-layer rock mass are the result of the interaction of engineering geological, hydrogeological conditions, and mining conditions of overlying rock under a natural state. However, it is difficult to predict the water inrush source and water inrush channel by geophysical prospecting or drilling, so the evolution mechanism of water inrush needs to be further studied. In view of the current domestic water inrush research, a large number of scholars analyze the evolution mechanism of water inrush through on-site monitoring, numerical simulation, similar simulation, theoretical analysis, and other methods [5–10]. The results show that the composite materials of similar simulation materials are relatively mature, but the evolution process of similar simulation water inrush is limited to microscopic rock samples; macroscopic-scale experimental research is less common and needs to be studied further [11,12]. As an auxiliary method for the macroscopic study of water inrush, numerical simulation has achieved certain research results [13,14]. Due to the influence of complex geological conditions and working to face mining through on-site physical methods or geophysical detection methods, it is not possible to accurately measure the dynamic changes of each parameter at the measuring point, so there is still a gap between the numerical simulation research and the real water inrush situation research results. In the theoretical research on mine water inrush, most focus on the study of water inrush from overlying strata and floor water inrush [15–17], paying more attention to the prediction method of water inrush and water inrush disaster management; the majority of scholars have achieved fruitful results in this regard [18,19]. The research on water inrush disasters abroad mainly focuses on the prediction and evaluation methods of water inrush [20–22], as well as the research on floor waters inrush disasters and the development law of water inrush fissure in overlying strata [23,24], which has been widely used in field practice. Secondly, during the mining process of the working face, a large number of studies have been carried out on the development height of the water fracture zone in the overlying strata, and the research results are relatively mature [25–27]. The research on seepage and water inrush of coal and rock mass in fine and micro aspects mainly focuses on the distribution characteristics and evolution law of fracture waters pressure and applies safety evaluation in combination with field practice [28–31]. For the study of the mechanism of mine water inrush, the overall research is insufficient. Because of the influence of mining geological conditions and coal mining methods, the mechanism of mine waters inrush and its disaster control should be studied in depth [32–34].

Therefore, based on the shortcomings of domestic and foreign scholars on water inrush and research of interlayer rock mass, this paper only studies the mechanism of water inrush under the influence during the mining of a close-distance coal seam working face. Because the rock mass between the close coal seams is greatly affected by the mining of the upper and lower coal seams, it plays a key role in the occurrence of mine water inrush disasters. Therefore, this paper takes the water inrush of interlayer rock mass between the 2<sup>–2</sup> coal seam and 3<sup>–1</sup> coal seam in Hanjiawan Coal Mine as the main research object, analyzes the fracture characteristics of interlayer rock mass structure and the development law of water inrush fractures under the geological conditions of the close coal seam, then determines the characteristics of water inrush channel of interlayer rock mass,

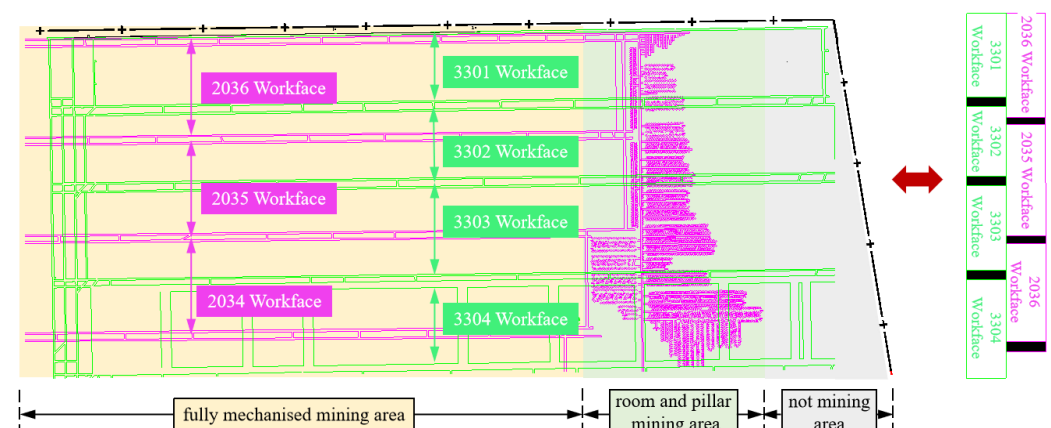
constructs the water inrush-solid coupling calculation model of interlayer rock mass in the close coal seam, analyzes the movement process of different flow state water in the flow-solid coupling calculation model, and determines the mechanism of the water inrush disaster of the interlayer rock mass. This paper mainly studies the following three aspects: (1) the characteristics and classification of water inrush channels formed by interlayer rocks mass affected by mining. (2) Based on the characteristics and classification of water inrush channels, a water-solid coupling calculation model of inter-layer rock mass is constructed. (3) Based on the fluid-solid coupling model, combined with the theory of fluid dynamics, the water inrush motion of plate flows, fracture flow, and pore fracture flow is transformed and solved.

## 2. Study Area and Objectives

The Hanjiawan Coal Mine is located in the northern part of the ShenFu mining area. The mine has a production capacity of 4.0 Mt/a and mines three seams, namely the  $2^{-2}$  seam,  $3^{-1}$  seam, and  $4^{-2}$  seam, with the  $3^{-1}$  seam near completion and the  $4^{-2}$  seam in the primary stage. Seam production is gentle, and the seams are nearly horizontal, with an inclination of approximately  $1\sim3^\circ$ . The seams are mined in a downward direction.

The  $2^{-2}$  coal seam is located in the upper part of the fourth section of the Yan'an Group. The thickness of the coal seam ranges from 0.5 to 5.5 m, with an average of 4.06 m. The average depth of the coal seam is 80 m, with a recoverable area of  $11\text{ km}^2$ . The thickness of the coal seam thins from west to east. The eastern boundary of the well field is the not mining area along the coal seam strike of 418 m. The room and pillar mining area is located between the long-wall mining area and the not mined area within a width of 135 to 550 m. The long-wall mining area is located to the west of the room-and-pillar mining area. The working face is 268 m long, with a mining height of 4 m and a strike length of 1820 m. The working face uses fully mechanized coal mining with a long wall, mining the entire height at once and managing the roof of the mining area by the collapse method.

The thickness of the  $3^{-1}$  coal seam is 2.1~3.4 m, with an average of 2.9 m. The recoverable thickness is 1.5~3.4 m, with average of 2.95 m. The burial depth is 101.50~157.07 m, and the recoverable area is  $12.77\text{ km}^2$ . The geological structure of the coal seam is simple; locally, it contains a layer of a band of approximately 0.3 m thickness, and the lithology of the band is mainly sandstone. The relationship between the upper and lower coal seams is shown in Figure 1, and the physical and mechanical parameters of the coal seams are shown in Figure 2. The overall research framework structure is shown in Figure 3.



**Figure 1.** Plane section location drawing of coal seam  $2^{-1}$  and  $3^{-1}$  in the study area.

There are two reservoirs of the surface within the Hanjiawan coal mine well-field, one with an area of  $9280\text{ m}^2$  and the other with an area of  $7876\text{ m}^2$ , half of which is within the Hanjiawan well-field. The average depth of water in the reservoirs is 1.8 m, and the depth of water can reach approximately 3 m during a period of abundant water. The total volume of water accumulated in the two reservoirs during the period of abundant water can reach

51,468 m<sup>3</sup>, forming a potential source of water for inrush water disasters. The northern part of the well field, approximately 1.5 km from the Bu Bag Trench to Liu Gen Ditch, is a water-rich area; the upper reaches are Bu Bag Trench wetlands.

| Stata                | Lithology | Thickness /m | Depth /m | Density (kg/m <sup>3</sup> ) | Compressive strength/MPa | Strength of extension/MPa | Elasticity modulus/MPa | Cohesion /GPa | Poisson ratio |
|----------------------|-----------|--------------|----------|------------------------------|--------------------------|---------------------------|------------------------|---------------|---------------|
| Silver sand          |           | 4.55         | 4.55     | 1850                         | 0.9                      | 0.05                      | 145                    | 0.25          | 0.05          |
| Clay                 |           | 18.13        | 22.68    | 1800                         | 2.8                      | 0.1                       | 548                    | 0.98          | 0.08          |
| Siltstone            |           | 1.05         | 23.73    | 2680                         | 28.36                    | 3.95                      | 1420                   | 5.1           | 0.25          |
| Post stone           |           | 1.47         | 25.20    | 2650                         | 23.3                     | 4.25                      | 3765                   | 4.3           | 0.23          |
| Mudstone             |           | 1.42         | 26.62    | 2461                         | 21.12                    | 1.77                      | 1115                   | 3.6           | 0.29          |
| Post stone           |           | 5.99         | 32.61    | 2650                         | 23.3                     | 4.25                      | 3765                   | 4.3           | 0.23          |
| Medium sandstone     |           | 2.15         | 34.76    | 2700                         | 32.4                     | 2.5                       | 6214                   | 4.8           | 0.19          |
| Post stone           |           | 4.64         | 39.40    | 2650                         | 23.3                     | 4.25                      | 3765                   | 4.3           | 0.23          |
| Mudstone             |           | 2.80         | 42.20    | 2461                         | 21.12                    | 1.77                      | 1115                   | 3.6           | 0.29          |
| Post stone           |           | 0.80         | 43.0     | 2650                         | 23.3                     | 4.25                      | 3765                   | 4.3           | 0.23          |
| Sandy mudstone       |           | 1.69         | 44.69    | 2487                         | 20.63                    | 1.85                      | 2875                   | 4.7           | 0.24          |
| Post stone           |           | 4.80         | 49.49    | 2650                         | 23.3                     | 4.25                      | 3765                   | 4.3           | 0.23          |
| Sandy mudstone       |           | 2.60         | 52.09    | 2487                         | 20.63                    | 1.85                      | 2875                   | 4.7           | 0.24          |
| Mudstone             |           | 2.80         | 54.89    | 2461                         | 21.12                    | 1.77                      | 1115                   | 3.6           | 0.29          |
| Medium sandstone     |           | 16.04        | 70.93    | 2700                         | 32.4                     | 2.5                       | 6214                   | 4.8           | 0.19          |
| Post stone           |           | 2.80         | 73.73    | 2650                         | 23.3                     | 4.25                      | 3765                   | 4.3           | 0.23          |
| Sandy mudstone       |           | 0.97         | 74.70    | 2487                         | 20.63                    | 1.85                      | 2875                   | 4.7           | 0.24          |
| 2 <sup>-2</sup> coal |           | 4.30         | 79.0     | 1423                         | 15.65                    | 0.85                      | 1376                   | 2.2           | 0.28          |
| Siltstone            |           | 2.78         | 81.78    | 2680                         | 28.36                    | 3.95                      | 1420                   | 5.1           | 0.25          |
| Sandy mudstone       |           | 2.42         | 84.20    | 2487                         | 20.63                    | 1.85                      | 2875                   | 4.7           | 0.24          |
| Siltstone            |           | 3.88         | 88.08    | 2680                         | 28.36                    | 3.95                      | 1420                   | 5.1           | 0.25          |
| Mudstone             |           | 4.35         | 92.43    | 2461                         | 21.12                    | 1.77                      | 1115                   | 3.6           | 0.29          |
| Post stone           |           | 12.0         | 104.43   | 2650                         | 23.3                     | 4.25                      | 3765                   | 4.3           | 0.23          |
| Medium sandstone     |           | 4.30         | 108.73   | 2700                         | 32.4                     | 2.5                       | 6214                   | 4.8           | 0.19          |
| 3 <sup>-1</sup> coal |           | 2.90         | 112.93   | 1428                         | 16.45                    | 1.05                      | 1385                   | 2.2           | 0.28          |
| Siltstone            |           | 2.83         | 115.76   | 2680                         | 28.36                    | 3.95                      | 1420                   | 5.1           | 0.25          |

Figure 2. The whole work of a schematic figure.

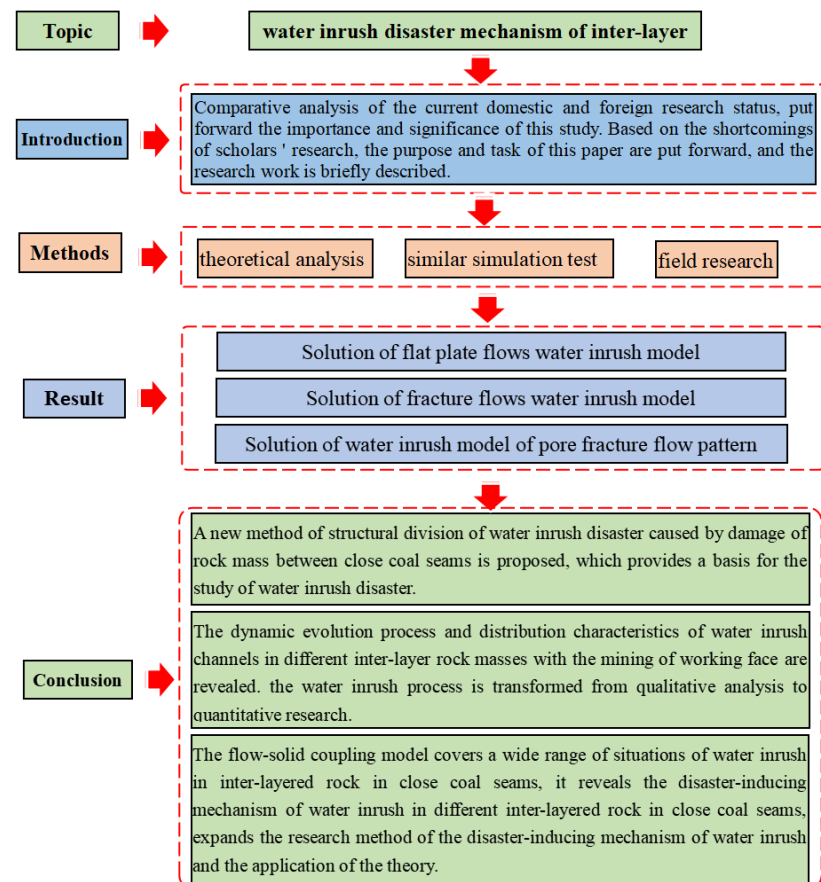


Figure 3. Physical and mechanical geological characterization and geological histogram.

The exploration data show that the water-bearing rock section from 2<sup>-2</sup> to 3<sup>-1</sup> coal has a thickness of 29.08~56.66 m, with an average thickness of 39.24 m. Some boreholes show

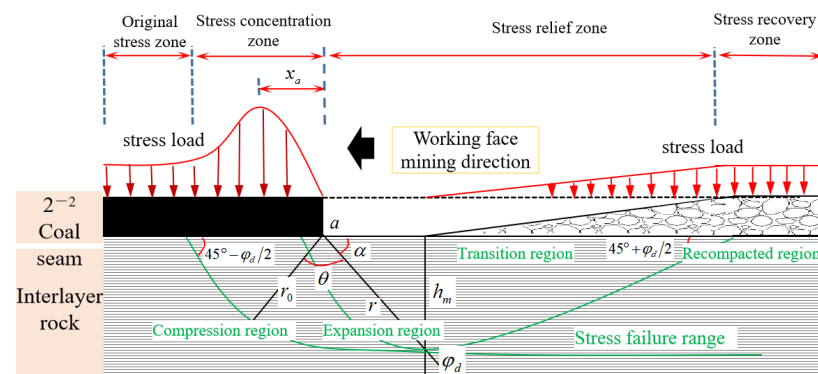
water gushing and leaking at the roof of the 3<sup>-1</sup> coal seam, indicating that the fracture development is uneven and does not constitute the same saturated water-bearing layer. The Middle Jurassic Zoro Formation and Yan'an Formation weathered rock fracture water-bearing rock groups are widely distributed and thick. With small spacing from the 2<sup>-2</sup> coal seam, the height of the coal mining inrush waters fracture zone will be directly penetrated, which is the main water-filled layer of the mine. In areas where the thickness of the loose sand layer is large, the diving of the loose rock type of the Fourth Series and the fracture water of the over rock of the coal system are the main sources of water filling in the mine. The normal surge volume of water throughout the Hanjiawan coal mine is 461 m<sup>3</sup>/h, and the maximum surge volume is 600 m<sup>3</sup>/h; there is water accumulation in old hollow areas in some areas with a surge volume of around 10 m<sup>3</sup>/h. The surge dynamics increase the expansion of the mining area. Based on the above field research and analysis, it can be seen that there is a potential risk of inrush water disasters in the Hanjiawen coal mine and the surrounding mines, so it is important to study the mechanism of the occurrence of inrush water disasters from inter-layer rock instability.

### 3. Structural Classification of Inter-Layered Rock and Characterization of Inrush Water Channels

#### 3.1. Discriminant Analysis of Structural Damage to Inter-Layered Rock

Under the disturbance of upper and lower coal seam mining in the close coal seam, the different structures formed by the fracture and instability of inter-layer rock mass are the direct influencing factors of mine water inrush disasters. Therefore, it is very important to analyze the damage degree and damage depth of inter-layer rock structures. Based on the stress effect and failure depth of the upper coal seam mining on the inter-layer rock, the development height of cave zones and water inrush fracture zones of lower coal seam mining on the inter-layer rock, the structural fracture, and damage degree of the inter-layer rock are analyzed. The schematic diagram of stress and damage depth of inter-layer rock in upper coal seam mining are shown in Figure 2.

Based on the elasticity theory and the Moore–Coulomb strength criterion, the damage depth of the inter-layered rocks by mining the upper group of coal seams during long-wall fully mechanized coal mining is calculated and analyzed according to the slip line calculation theory. The process of inter-layered rock damages is shown in Figure 4.



**Figure 4.** Schematic diagram of the stresses and depth of damage in the inter-layer of the upper group of coal seam mining.

The logarithmic double helix equation for  $r$ ,  $r_0$ , can be expressed as:

$$r = r_0 e^{\theta \tan \varphi_d}. \quad (1)$$

Approximating the curve in part of the region in Figure 4 as a straight line of the solution, the geometric relationship to the figure provides:

$$r_0 = x_a / 2 \cos\left(\frac{\pi}{4} + \frac{\varphi_d}{2}\right), \quad (2)$$

$$\alpha = \frac{\pi}{2} - \left( \frac{\pi}{4} - \frac{\varphi_d}{2} - \theta \right), \quad (3)$$

$$\sin \alpha = \cos \left( \alpha - \frac{\pi}{2} \right), \quad (4)$$

$$h_m = r \sin \alpha. \quad (5)$$

The equation based on the cohesion of the coal seam  $C$  as parameter  $x_a$  is:

$$x_a = \frac{M}{2\eta \tan \varphi} \ln \frac{k\gamma H + C \tan \varphi}{\eta C \tan \varphi}. \quad (6)$$

Substituting Equations (1)–(4) and (6) into Equation (5) according to the basic parameters of coal rock mechanics, the maximum depth of damage  $h_m$  to the bottom slab can be obtained as follows:

$$h_m = \frac{M \cdot \cos \varphi_d}{4\eta \cdot \tan \varphi \cdot \cos \left( \frac{\pi}{4} + \frac{\varphi_d}{2} \right)} e^{\left( \frac{\pi}{4} + \frac{\varphi_d}{2} \right) \tan \varphi_d} \cdot \ln \frac{k\gamma H + C \cdot \cot \varphi}{\eta \cdot C \cdot \cot \varphi}, \quad (7)$$

where  $M$  is the mining height of the coal seam, m;  $k$  is the stress concentration factor;  $\varphi$  is the internal friction angle of the coal seam, °;  $H$  is the mining depth, m;  $\eta = \frac{1+\sin \varphi}{1-\sin \varphi}$  is the triaxial stress factor;  $\gamma$  is the average capacity weight of the overlying rock seam, kN/m<sup>3</sup>;  $\varphi_d$  is the internal friction angle of the inter-layered rock, °;  $C$  is the cohesion of the coal seam, MPa;  $x_a$  is the length of the yield region of the coal seam, m.

According to the mechanical parameters of the rock seam of the upper group 2<sup>-2</sup> coal in Figure 4, the geological conditions in which the mine is located, the analysis, and calculation of the damage depth of the rock seam between the layers during the long-wall fully mechanized coal mining of the upper group coal, the mining height of the 2<sup>-2</sup> coal  $M = 4.3$  m, the internal friction angle of the rock layer  $\varphi_d = 30^\circ$ , the triaxial stress coefficient  $\eta = \frac{1+\sin 36^\circ}{1-\sin 36^\circ} = 3.88$  of the overlying rock layer, the internal friction angle  $\varphi = 36^\circ$  of the coal seam, the stress concentration coefficient  $k = 2.4$  of the upper group coal, the average capacity weight  $\gamma = 25$  kN/m<sup>3</sup> of the overlying rock layer, the burial depth of the upper group coal  $H = 80$  m, and the cohesive force of the coal seam  $C = 2.2$ . Substituting each parameter into Equation (7):

$$h_m = \frac{4.3 \times \cos 30^\circ}{4 \times 3.88 \times \tan 36^\circ \times \cos \left( \frac{\pi}{4} + \frac{\pi}{6} \right)} e^{\left( \frac{\pi}{4} + \frac{\pi}{6} \right) \tan 30^\circ} \times \ln \frac{2.4 \times 25 \times 80 + 2.2 \times \cot 36^\circ}{3.88 \times 2.2 \times \cot 36^\circ} = 0.28 \text{ m}.$$

In the process of lower coal seam mining, the inter-layer rock structure is unstable and collapses under the action of overload stress and self-weight stress, and the inter-layer rock fractures are further developed under repeated disturbance. Therefore, the cave height of inter-layer rock in lower coal seam mining is calculated and analyzed. When the lower coal seam is mined, the upper coal seam collapses to form a gob. Therefore, when calculating the height of the overburden fracture zone and the cave zone of the lower coal seam, the comprehensive mining height  $M_Z$  should be used instead of the single coal seam mining height  $M$ . Then,  $M_Z$  and ‘two zones’ can be expressed as follows according to the ‘three under’ coal mining operation procedures:

$$M_Z = M_2 + \left( M_1 - \frac{L}{y_2} \right), \quad (8)$$

where  $M_1$  is the mining height of the upper coal seam, m;  $M_2$  is the mining height of the lower coal seam, m;  $L$  is the distance from the rock between the seams, m;  $y_2$  is the ratio of the mining collapses height of the mining height of the lower coal seam.

By analyzing the fracture development height of inter-layer rock in the process of repeated mining of the lower coal seam, the calculation method of the development height of ‘cave zone’ and ‘water inrush fracture zone’ of over strata under the repeated disturbance of

lower coal seam can be used for reference. By comparing and analyzing the development height of ‘two zones’ and the thickness of inter-layer rock, the fracture development height of inter-layer rock under repeated disturbance of lower coal seam can be determined. It provides a basis for the classification of inter-layer rock structure and the coupling mechanism of water inrush from inter-layer rocks in the mining process of upper and lower coal seams.

The ratio of cave height to mining height in Equation (2) can be calculated in Table 1. Secondly, according to the above table, the height of the cave zone and water inrush fracture zone of the upper coal seam  $H_{k1}$  and  $H_{li1}$  and the height of the cave zone of the lower coal seam  $H_{k2}$  are calculated, then the relationship between them and the distance  $L$  from inter-layer rocks is compared to determine the thickness relationship between the cave zone and inter-layer rock after lower coal seam mining. Therefore, the mining height  $M$  of Table 1 is replaced by the comprehensive mining height  $M_Z$  to calculate the initial fracture zone height  $H_{li2}$  of the lower coal seam. The height of the ‘two zones’ of the lower coal seam should be added to the height of the ‘two zones’ of the upper coal seam. Finally, the height of the ‘two zones’ of the lower coal seam takes the maximum of the surface height of the upper and lower coal seams. The specific calculation is shown in Equation (9).

$$\begin{aligned} H_{k2}' &= \max[H_{k1} + L + M_1, H_{k2}] \\ H_{li2}' &= \max[H_{li1} + L + M_1, H_{li2}] \end{aligned} \quad (9)$$

**Table 1.** Fracture development height of inter-layer rock mass under repeated mining.

| “Two-Band”         | Lithology   | Suitable for $M \leq 3$ m Coal Seam  | “Two-Band”                                | Lithology   | Suitable for $M \leq 3$ m Coal Seam      |                            |
|--------------------|-------------|--------------------------------------|-------------------------------------------|-------------|------------------------------------------|----------------------------|
|                    |             | Formula One                          |                                           |             | Formula One                              | Formula Two                |
| caving zone height | stiffness   | $H_k = \frac{100M}{2.1M+16} \pm 2.5$ | height of fractured water-conducting zone | stiffness   | $H_{li} = \frac{100M}{1.2M+2.0} \pm 8.9$ | $H_{li} = 30\sqrt{M} + 10$ |
|                    | medium-hard | $H_k = \frac{100M}{4.7M+19} \pm 2.2$ |                                           | medium-hard | $H_{li} = \frac{100M}{1.6M+3.6} \pm 5.6$ | $H_{li} = 20\sqrt{M} + 10$ |
|                    | weakness    | $H_k = \frac{100M}{6.2M+32} \pm 1.5$ |                                           | weakness    | $H_{li} = \frac{100M}{3.1M+5.0} \pm 4.0$ | $H_{li} = 10\sqrt{M} + 5$  |
|                    | very soft   | $H_k = \frac{100M}{7.0M+63} \pm 1.2$ |                                           | very soft   | $H_{li} = \frac{100M}{5.0M+8.0} \pm 3.0$ | --                         |

Note:  $M$  is the effective mining height, the lithology strength is classified according to the uni-axial compressive strength of the rock, with 40–80 MPa for hard, 20–40 MPa for medium-hard, 10–20 MPa for soft, and 10 MPa or less for very soft.

The calculation of the cave zone of the inter-layer rocks and the water inrush fracture zone of the inter-layer rock in the lower coal seam of the close distance coal seam is affected by the softening effect of the water accumulation in the upper coal seam gob and the hinged structure of the upper part of the inter-layer rock. The height of the fracture zone of the inter-layer rock mass is the maximum of the height of the water inrush fracture zone of the inter-layer rock plus the bending sinking hinge thickness  $H_c$ . The specific calculation is shown in Formula (10).

$$\begin{aligned} H_{k2}' &= H_{k2} \\ H_{li2}' &= \max[H_{li1} + L + M_1 + H_c, H_{li2} + H_c] \end{aligned} \quad (10)$$

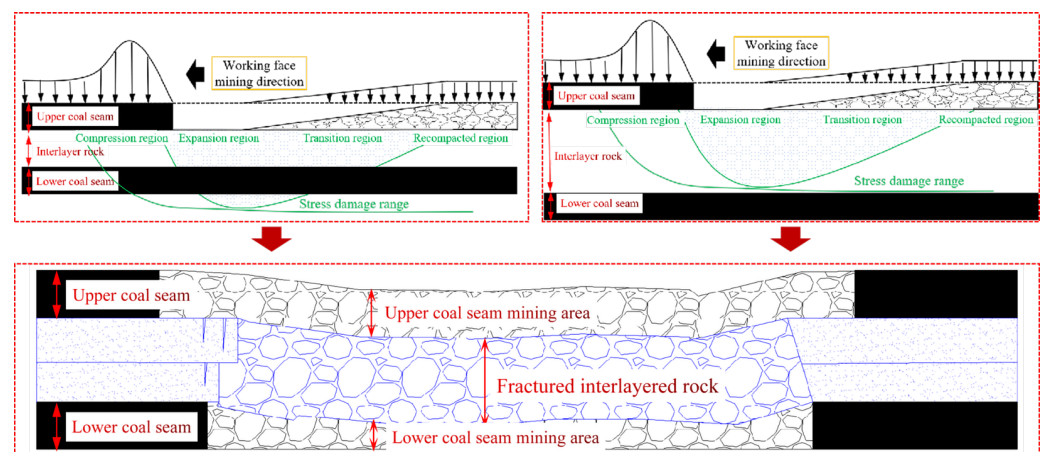
### 3.2. Inter-Layer Rocks Structure Classification

#### 3.2.1. Completely Fractured Inter-Layer Rock

During the mining process of the upper and lower coal seam working faces, the inter-layer rock structure is completely broken. Such coal seams are mostly very close to each other, or the inter-layer rock has been completely destroyed in the upper coal seam mining; there is no thick bearing layer structure in the inter-layer rock. According to the calculation formula for damage depth of inter-layer rock, when the thickness of inter-layer rock mass is less than or equal to the depth of complete damage and fracture, that is  $L \leq h_m + H_{k2}'$ . The complete damage and fracture depth refers to the sum of the damage depth of the upper coal seam mining on the floor of the inter-layer rock and the height of the cave zone

of the lower coal seam mining. Under the influence of the mining of the upper and lower coal seam working faces, the inter-layer rock is fractured to form a block, and the integrity is very poor. In the process of lower coal seam mining, it is easy to form a roof fall; the formation of a cave channel causes the cave rock block of the upper coal seam gob to move to the lower coal seam gob. When the thickness of the inter-layer rock is basically equal to the depth of damage and fracture, the diameter of the lower rock after the failure of the inter-layer rock is obviously larger than that of the upper rock mass. After the mining of the upper and lower coal seams, the possibility of gangue collapses in the gob decreases, and no effective bearing structure is formed.

The completely broken inter-layer rock is completely broken under the action of roof stress during the mining process of the upper coal seam or the mining process of the lower coal seam. The fractures are fully developed, forming a water inrush flow channel in the upper water-accumulated gob. The development density of water inrush fractures reaches the maximum, which can be regarded as a spatial network model with complete penetration of longitudinal and transverse fractures. The permeability characteristics of transverse separation fractures are the same as those of longitudinal fracture fractures, including the permeability characteristics of longitudinal and transverse water inrush fractures formed by boundary fracture of inter-layer rock and water inrush fractures in the middle of the inter-layer rock. As shown in Figure 5.



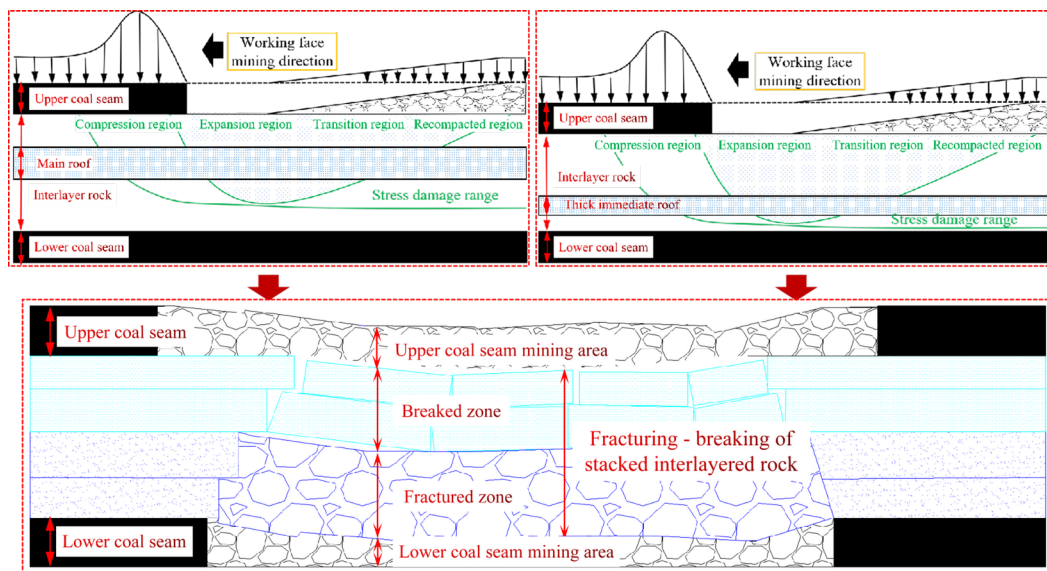
**Figure 5.** Completely broken inter-layer rock structure diagram.

### 3.2.2. Fractured–Broken Stacked Inter-Layer

Based on the failure depth of the upper coal seam mining to the floor and the calculation theory of the height of the ‘two zones’ in the lower coal seam mining, the thickness of the fractured–broken stacked inter-layer rock is greater than the thickness of the completely fractured inter-layer rock; that is,  $L \geq h_m + H_{k2}'$ , where most of them are thick immediate roof shallow buried close distance coal seams or main roof completely damaged shallow buried close distance coal seams. During the mining process of the upper and lower coal seam working faces, the inter-layer rock has a thicker immediate roof or a bearing inter-layer main roof; the fractured–broken stacked inter-layer rock structure is more complete than the completely fractured inter-layer rock. When the upper and lower coal seams are mined, due to the existence of a thick immediate roof or the main roof structure of layers, the inter-layer rock will not form a completely fractured state; a fault zone will be formed into the upper part of the inter-layer rock or the lower part of the inter-layer rock. When the coal seam is a thick immediate roof shallow buried close distance coal seam, the upper part of the inter-layer rock is the lower part of the broken zone, which is the fracture zone. When the coal seam is a shallow buried close-distance coal seam with complete damage to the main roof, the upper part of the inter-layer rock is the lower part of the fracture zone, which is the broken zone. The diameter of the fracture zones and the block of the broken

zone is larger than that of the completely fractured rock, and the fracture development density is smaller than that of the completely fractured rock.

Under the action of roof stress in the mining process of the upper coal seam or the mining process of the lower coal seam, the fracture development degree of the fractured-broken composite inter-layer rock is obviously smaller than the completely fractured inter-layer rock, but the water inrush channel of the upper water gob is also formed. The fracture zone can be regarded as a spatial network model with complete penetration of longitudinal and transverse fractures, but the unit size of the spatial network model is larger than the completely fractured inter-layer rock. The fracture zone in the fractured-broken laminate inter-layer rock mass can be regarded as the same as the permeability characteristics of the transverse separation fracture and the longitudinal fracture, and the permeability of the transverse separation fracture in the fracture zone is smaller than that of the longitudinal fracture. The vertical and horizontal waters inrush fractures formed by the boundary fracture of the inter-layer rock in the fracture zone are exactly the same as the permeability characteristics of the water inrush fractures in the middle of the gob, while the permeability of the boundary fractures in the broken zone is obviously larger than that in the middle of the gob. As shown in Figure 6.

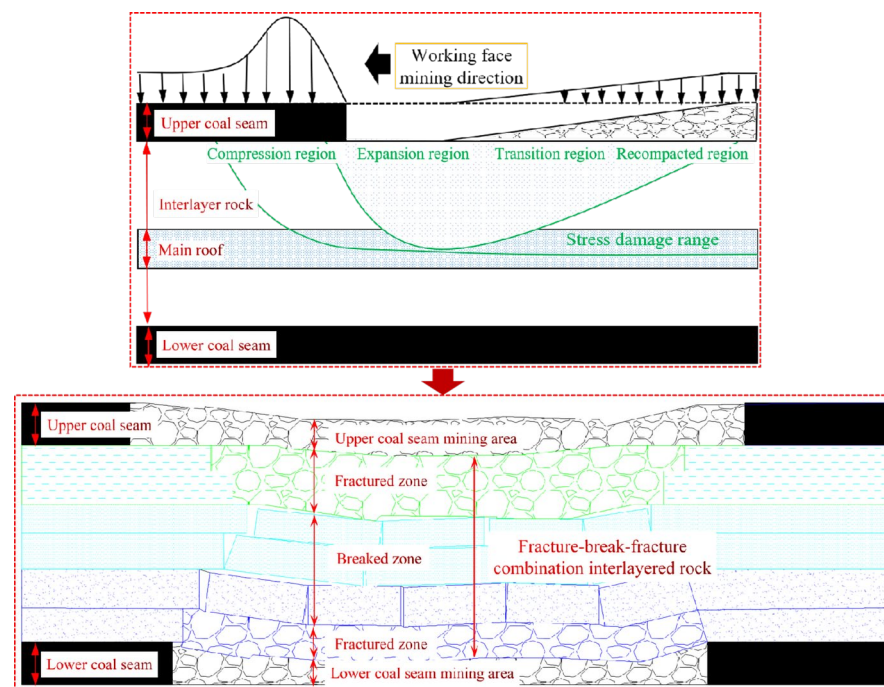


**Figure 6.** Schematic diagram of rock mass structure between crushing–breaking stacked layers.

### 3.2.3. Fractured–Broken–Fractured Combined Inter-Layer Rock

According to the failure depth of upper coal seam mining to the floor and the calculation theory of the height of the ‘two zones’ in lower coal seam mining, the thickness of the rock between the fractured–broken–fractured combination inter-layer is greater than the sum of the floor failure depth and the water inrush fracture zone, that is,  $L \geq h_m + H_{li2}'$ , and it is a shallow buried close-distance coal seam with partial damage to the main roof. During the mining process of the upper and lower coal seam working to face, due to the large distance between the layers and the existence of the main roof between the layers, the rock structure of the fractured–broken–fractured combination layer is more complete than the fractured–broken stacked layer. When the upper and lower coal seams are mined, the main roof is located in the failure zone of the upper coal seam floor, the upper and lower parts of the inter-layer rock form a fracture zone, and the main roof breaks to form a damaged rock block to form a mutually articulated ‘masonry beam’ structure. The block diameter of the fracture zone of the fracture–broken–fracture composite inter-layer rock is similar to the fracture–broken stacked inter-layer rock, but the fracture development density of the middle fracture zone is smaller than the fracture–broken stacked inter-layer rock.

In the process of upper coal seam mining and lower coal seam mining, the inter-layer rock of the fractured–broken–fractured combination is subjected to roof stress and the inter-layer rock of lower coal seam mining is collapsed and broken. The degree of fracture development is obviously smaller than that of fracture–broken stacked inter-layer rock, but it can form a water inrush channel in the upper water-accumulating gob. However, its water inrush capacity is obviously weakened. The upper and lower fracture zones of inter-layer rock can be regarded as a spatial network model with complete penetration of longitudinal and transverse fractures. The unit scale of the spatial network model is basically similar to the fracture–broken stacked inter-layer rock. The fracture zone in the inter-layer rock of the fractured–broken–fractured combination can be regarded as the same as the permeability characteristics of the transverse separation fracture and the permeability characteristics of the longitudinal fracture. The water inrush of the transverse separation fracture in the fracture zone is smaller than that of the longitudinal fracture, it is also smaller than that of the fractured–broken laminate inter-layer rock. The longitudinal and transverse water inrush fractures formed by the boundary fracture of the inter-layer rock in the fracture zone are exactly the same as the water inrush characteristics of the water inrush fractures in the middle of the gob. The water inrush of the boundary fractures in the fracture zone is obviously larger than that in the middle of the gob, but smaller than the fracture zone in the middle of the fractured–broken laminate inter-layer rock. As shown in Figure 7.



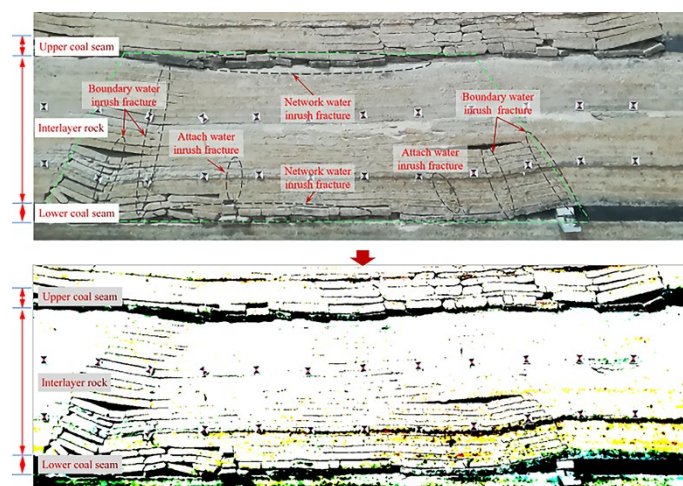
**Figure 7.** Broken–broken–broken combination inter-layer rock mass structure diagram.

### 3.3. Analysis of Water Inrush Channels Characteristics of Inter-Layer Rock

It is difficult to realize the direct monitoring or indirect measurement of the distribution characteristics of water inrush fractures in inter-layer rock. At present, the on-site monitoring methods of water inrush fractures in inter-layer rocks mainly include the geophysical detection method and the drilling detection method. Although there are many monitoring methods, the distribution characteristics of water inrush fractures in fractured rock can only reflect the local characteristics, or the accuracy is not enough; the overall characteristics of water inrush fractures cannot be fully reflected. The two-dimensional similar simulation test can better reflect the spatial and temporal evolution law and overall distribution characteristics of water inrush fractures in the inter-layer rock. Therefore, many scholars have studied the distribution characteristics of water inrush fractures in the inter-layer rock of shallow-buried close coal seams through similar simulation tests, which

can better fully reflect the development and evolution law and distribution characteristics of water inrush fractures in the inter-layer rock during the mining process of upper and lower coal seams.

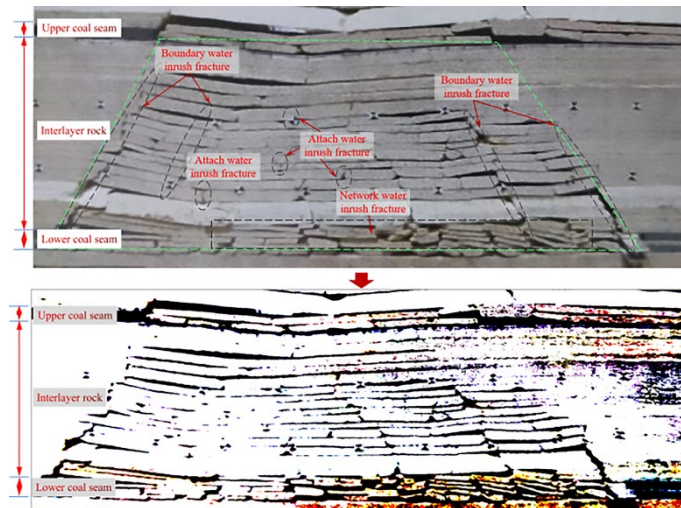
Figures 8–11 show the distribution characteristics of water inrush fractures in the inter-layer rock during a similar simulation test of the close-distance coal seams in four coal mines. The distribution area of water inrush fractures in the inter-layer rock presents a positive trapezoid as a whole. Combined with the classification of inter-layer rock structure, the classification of water inrush fractures can be obtained. Water inrush fractures mainly include network water inrush fractures, attach water inrush fractures, and boundary water inrush fractures. Due to the different thickness, lithology, mining height, and inter-mining ratio of inter-layer rock in each coal mine, the types of water inrush fractures in inter-layer rock are different. During the mining process of the upper and lower coal seam working faces, the network waters inrush fractures are mostly distributed in the upper part of the inter-layer rock and the lower part of the inter-layer rock, forming water inrush fractures with transverse separation fractures and longitudinal break fractures. The development degree of water inrush fractures is the most obvious, and the water inrush coefficient is large. The water inrush fractures at the boundary are mostly distributed on the side of the open-off cut and the side of the stop line along the advancing direction of the working face; that is, they are situated on both sides of the positive trapezoid of the inter-layer rock, forming transverse and longitudinal water inrush fracture that penetrates the whole inter-layer rock. The development degree of longitudinal fractures is greater than that of transverse fractures. The attach waters inrush fractures are mostly distributed in the middle area of the inter-layer rock. The development degree of longitudinal break fractures is greater than that of transverse separation fractures. The formation process is break–open–closure, and finally, the horizontal and longitudinal attach water inrush fractures are formed. The analysis shows that the characteristics of water inrush fractures in the inter-layer rock of four coal mines are similar and different.



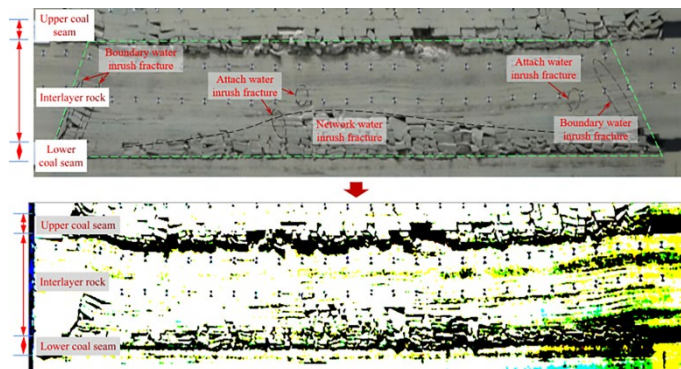
**Figure 8.** Distribution of water-conducting fractures in inter-layer rock of Anshan coal mine.

Through the analysis of the similar simulation experiment results of four close coal seam mines, it can be concluded that there are obvious differences in the distribution characteristics of water inrush fractures in inter-layer rock. During the mining process of the upper and lower coal seams in the Anshan coal mine, the stress of the upper coal seam on the floor (upper part of the inter-layer rock) forms a broken area. Combined with the collapse of the inter-layer rock structure during the mining process of the lower coal seam, a typical fractured–broken–fractured combined inter-layer rock structure is formed. When the upper water flows through the inter-layer rock, the network waters inrush fractures are formed into the upper and lower parts of the inter-layer rock, and the boundary water inrush fractures are formed on both sides of the positive trapezoid. The attach waters in-

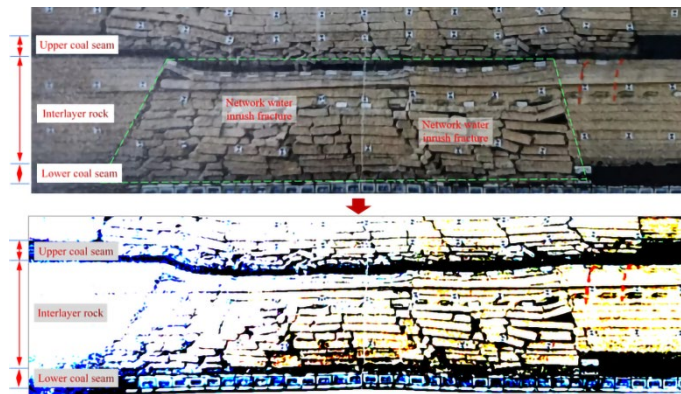
rush fractures are formed in the middle of the inter-layer rock, forming the inter-layer rock water inrush channel including the network water inrush fractures, the boundary waters inrush fractures, and the attach water inrush fractures. The development law and distribution characteristics of water inrush fractures in the inter-layer rock of Hanjiawan coal mine are similar to those of water inrush fractures in the inter-layer rock of Anshan coal mine, but there are differences. The development degree of water inrush fractures and the density of water inrush fractures in the upper and lower parts of the inter-layer rock in Hanjiawan is obviously larger than those in Anshan coal mine, and the development degree of water inrush fractures in the middle inter-layer rock is larger than that in Anshan coal mine.



**Figure 9.** Distribution of water-conducting fractures in inter-layer rock of Shangwan coal mine.



**Figure 10.** Distribution of water-conducting fractures in inter-layer rock of Hanjiawan coal mine.



**Figure 11.** Distribution of water-conducting fractures in inter-layer rock of Bulianta coal mine.

In the process of mining the upper and lower coal seams in Bulianta coal mine, the water inrush fractures in the inter-layer rock form an obvious network of water inrush fractures in the upper part of the inter-layer rock under the stress of the upper coal seam floor. Under the combined action of its own gravity and the stress of the over strata, the inter-layer rock forms a completely broken state. The water inrush current in the gob forms a typical network of water inrush fractures through the inter-layer rock, forming a water inrush channel through the inter-layer rock. During the mining process of the upper and lower coal seams in Shangwan coal mine, a fractured–broken stacked inter-layer rock structure was formed. When the water in the gob passed through the inter-layer rock, the middle and lower parts were network water inrush fractures, and the upper part formed a penetrating longitudinal attach fracture. The inter-layer rock formed multiple longitudinal water inrush channels with periodic weighting. Compared with Bulianta coal mine and Shangwan coal mine, the distribution characteristics of water inrush fractures in inter-layer rock are similar; the water inrush capacity and water inrush coefficient of inter-layer rock are larger.

The network water-inrush fracture and boundary water-inrush fracture are the main channels for the gob water, water-rich rock water, or separation water to flow into the lower coal seam working face or gob. Therefore, it is necessary to study the distribution law of network water-inrush fracture and boundary water-inrush fracture in the process of coal seam mining. Through the analysis of the characteristics of water-inrush channels in some mines in the northern Shaanxi mining area, it can be obtained that the distribution characteristics of water-inrush fracture in the middle-layer rock during the upper and lower coal seam mining process have the following characteristics: (1) the water inrush fracture area of inter-layer rock presents a ‘positive trapezoid’. (2) The water-inrush channels formed by network water-inrush fractures and boundary water-inrush fractures are the main channels for water-inrush from the gob of upper coal seam or water-rich strata to the lower coal seam. (3) The attach waters inrush fractures formed in the middle of the inter-layer rock are connected with the network water inrush fractures and the boundary waters inrush fractures, forming the secondary water inrush channel of the inter-layer rock. (4) The upper and lower part of the inter-layer rock, that is, the inter-layer rocks network close to the upper and lower coal seams, have a high density of water inrush fractures and dense water inrush channels.

By analyzing the distribution characteristics of water-inrush fracture channels in the inter-layer rock of the above coal mines, it can be concluded that the distribution characteristics of water-inrush fractures are the distribution characteristics of water-inrush channels in the inter-layer rock. In order to explore the mechanism of a water inrush disaster caused by inter-layer rock failure, it is necessary to analyze the flow law of gob water or water-rich rock water in the water inrush channel during the mining process of upper and lower coal seams; there are differences in the flow law of water when it moves in different water inrush fractures. Therefore, in this paper, the flow of water in the inrush fracture of inter-layer rock is divided into three categories, which are the flow of water in the water-inrush fracture, the flow of water in the boundary water-inrush fracture through the inter-layer rock, and the flow of water in the network water-inrush fracture area. The mechanism of the water-inrush disaster is also studied.

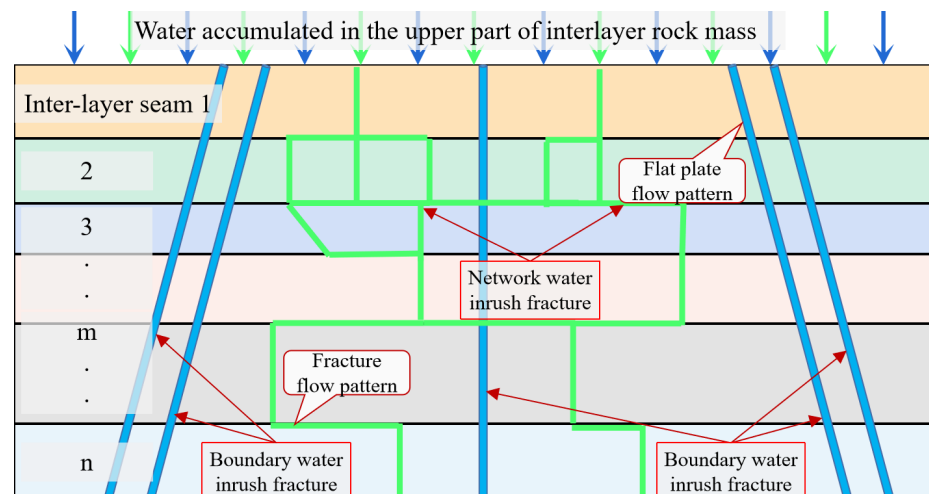
#### **4. Analysis of Fluid–Solid Coupling Disaster-Causing Mechanism**

##### **4.1. Fluid–Solid Coupling Calculation Models on Inter-Layer Rock**

Based on the distribution characteristics of water inrush fractures in inter-layer rock and the fracture structure of inter-layer rock, the water inrush calculation model of gob water or water-rich rock water in inter-layer rock after mining upper and lower coal seams is constructed. It can be divided into the network-boundary fluid–solid coupling water inrush calculation model and network-attach-boundary fluid–solid coupling water inrush calculation model, where the water movement in the process of a water-inrush disaster of inter-layer rock is analyzed.

#### 4.1.1. Network-Boundary Fluid–Solid Coupling Water Inrush Calculation Model

The inter-layer rock forms a complete fracture structure after the mining disturbance of the upper and lower coal seams. The formed water-inrush fractures are not a single form of network water-inrush fractures or boundary water inrush fractures, they include boundary water-inrush fractures and network water-inrush fractures at the same time. The water accumulated in the upper part of the inter-layer rock enters the lower gob or working face through the water-inrush fractures of the inter-layer rock with time and space synchronization. When the upper water flows through the network fractures, the flow path is more complicated; the probability of lateral movement is the same as that of longitudinal movement. It mainly moves along the lateral separation fractures and longitudinal broken fractures formed by the fracture of different inter-layer rock strata. The state of water flow inside can be regarded as a high-density fracture flow state; the area of water flow in the inter-layer rock is a fracture medium. Because the upper water flows into the gob in the process of this fracture flow, the flow time is short, and the effect of water on the network fracture is not obvious. Therefore, it is assumed that the water flow process has no effect on the distribution and state characteristics of the network water inrush fracture; the effect of water on the network fracture is ignored. The network-boundary water inrush calculation model is shown in Figure 12.



**Figure 12.** Network-boundary fluid–solid coupling water inrush calculation model.

The flow of water accumulated in the upper part of the inter-layer rock in the network water-inrush fracture belongs to Darcy flow, it is not flowing outside the network water inrush fracture; that is, the pore flow between water and different inter-layer rock layers is ignored. Although the network water-inrush fractures are not completely evenly distributed among the inter-layer rock due to the high density of its distribution, it can be regarded as a connected uniform fracture network. The inter-layer rock area of the network water inrush fractures is a continuous rock medium; that is, the physical equation of water flow in the network fractures can be equivalently expressed by the seepage flow equation of the porous medium. Although its essence is different, the difference between the two is mainly manifested in the great difference in the permeability coefficient. The permeability coefficient of a continuous medium depends on the stress and strain value of the rock, while the water inrush coefficient of water inrush fracture in an inter-layer rock network is related to the characteristics of fracture, which can be expressed by Formula (11). The fluid flow in the water inrush fracture of the network can be equivalently expressed as Equation (12) [35].

$$(k(b, f)p, i), i = n \frac{\partial p}{\partial t} + \frac{\partial e}{\partial t} + W, \quad (11)$$

$$k(b, f) = -\frac{1}{12} \sum_{i=1}^n b_i^3 f_i. \quad (12)$$

In the Formula,  $k$  is the equivalent permeability coefficient, and it can be calculated according to formula (12).  $b_i$  is the width of the fracture;  $f_i$  is the friction coefficient of the fracture;  $p$  is fracture water pressure;  $e$  is volume deformation;  $W$  is the source of water accumulation;  $t$  is time.

The flow process of water in the upper part of the inter-layer rock in the boundary water-inrush fracture is instantaneous, and the water inflow is large. The distribution characteristics of water-inrush fractures at the boundary of inter-layer rock show that there are water-inrush channels longitudinally penetrating multiple inter-layer rock layers at the side of the open-off cut, the side of the stop-mining line, and the middle position of the strike in the lower coal seam. The distribution characteristics of water inrush fractures in inter-layer rock are obtained by the above similar simulation test. Multiple boundary water-inrush fracture channels can be found. These boundary water-inrush fracture channels can make the gob water-inrush into the lower coal seam working face or gob, and in a short time, become the main flow channel of the upper water inrush into the lower coal seam. The flow state of the upper waters in the boundary waters-inrush fracture is flat flows. In this paper, the Darcy-Weisbach equation is used to express the flow state of water in the boundary water-inrush fracture through multiple inter-layered rock masses, as shown in Equation (13).

$$\Delta H = f \times \frac{l}{\bar{d}} \times \frac{v_w^2}{2g}. \quad (13)$$

In the formula,  $\Delta H$  is the head loss;  $\bar{d}$  is the average inner diameter of the inrush water channel;  $l$  is the length of the inrush channel;  $g$  is the acceleration of gravity;  $u$  is the velocity of water flow;  $f$  is the friction system (dimensionless); it can be calculated based on the Nikuradse experimental curve, as shown in Equation (14).

$$f = \begin{cases} 1/[1.74 + 2\lg(2\Delta/d)]^2, & \text{Re} > 100,000 \\ 64/\text{Re}, & \text{Re} < 2300 \\ 0.326/\text{Re}^{0.25}, & 2300 < \text{Re} < 100,000 \end{cases}. \quad (14)$$

If the porosity of the boundary waters inrush channel is 1, then  $v = u$ ,  $J = \Delta H/l$ , and, based on Equation (13), can be transformed into:

$$v = \frac{2gd}{fv} \times J. \quad (15)$$

In order to facilitate the numerical simulation calculation, the equivalent water-inrush coefficient is calculated according to Formula (15), where  $v$  is the water flow velocity of the boundary waters inrush fracture [36].

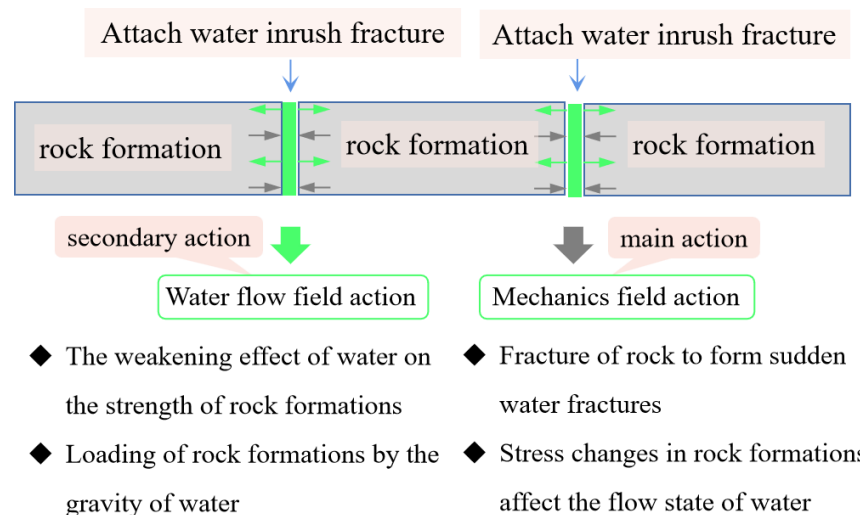
$$K_d = \frac{2gd}{fv}. \quad (16)$$

Therefore, the inter-layer rocks network-boundary fluid–solid coupling water inrush calculation models mainly include the flow process of the upper water accumulation of the inter-layer rock in the network water inrush fracture and the boundary waters inrush fracture. The nonlinear flow equation is used to describe the flow process of the upper water accumulation in the inter-layer rock water inrush fracture. The fracture flows state and the plate flow state are used to analyze the mechanism of water inrush and the disaster of inter-layer rock failure.

#### 4.1.2. Network-Attach-Boundary Fluid–Solid Coupling Water Inrush Calculation Model

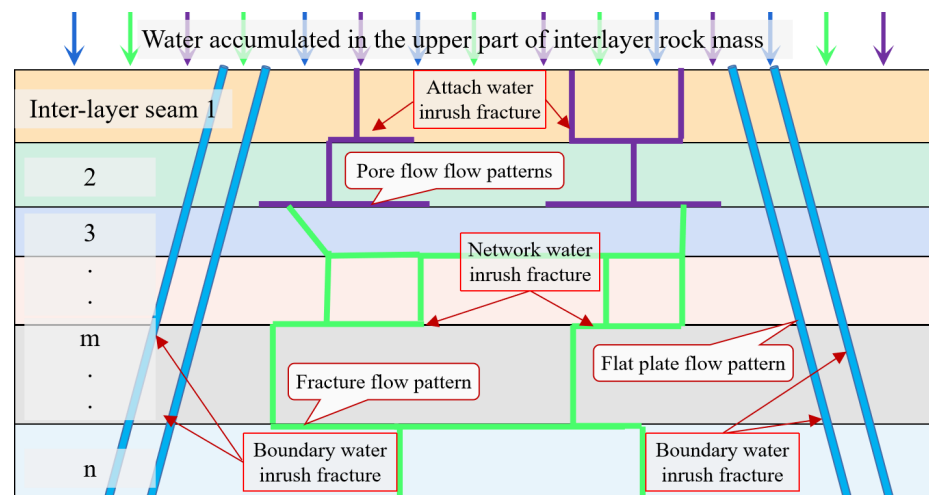
The inter-layer rock forms a fracture–broken–fracture combination structure after the mining disturbance of the upper and lower coal seams, including the boundary water inrush fracture, the network water inrush fracture, and the attach water inrush fracture.

When the gob water flows through the network water inrush fracture and the boundary water inrush fracture, it has the characteristics of short time and fast flow, so the interaction between water and inter-layer rock is ignored. When the gob water moves in the water inrush fracture, the interaction between water and inter-layer rock must be considered because of its long action time with water and the characteristics of water inrush fracture. The movement process of water in the fracture of water inrush in the inter-layer rock mainly includes two kinds of physical media: water and rock. The flow of water in the fracture is the interaction of two kinds of media. It is necessary to consider the mechanical effect and physical softening of water on the rock layer. It is also necessary to consider the influence of the change in water inrush fracture caused by the change in inter-layer rock structure of the water flow, mainly in the form of water inrush and flow pattern. The main effect of water accumulation in the upper part of the inter-layer rock is the softening of the rock mass strength and the load generated, while the effect of the inter-layer rock on the water is mainly that the mining of the upper and lower coal seams causes fractures in the inter-layer rock. The change in the mechanical field affects the change in the water inrush fracture. The flow of water changes due to the change in the water inrush fracture, which ultimately affects the water inrush coefficient in the water inrush fracture. The coupling mechanism between water and rock strata is shown in Figure 13.



**Figure 13.** Schematic diagram of fluid–solid coupling mechanism of water-conducting fracture.

When the water in the gob flows in the inter-layer rock containing boundary water inrush fractures, network water inrush fractures, and attach water inrush fractures at the same time, the network-attaching-boundary waters inrush calculation model is different from the model containing only boundary water inrush fractures and network water inrush fractures. It is necessary to analyze the interaction between water and inter-layer rock in attaching water inrush fractures, the flow of water in network waters inrush fractures, and boundary water inrush fractures can refer to the first type of water inrush calculation model. When the water flows in the water inrush fracture, the effect of watering on the rock layers changes the physical characteristics of the inter-layer rock layer and exerts a load on the inter-layer rock layer. The fracture and extrusion of inter-layer rock strata change the characteristics of water inrush fractures and then affect the water inrush characteristics of water, forming a functional relationship between the water inrush coefficient and stress–strain. Therefore, the network-attaching-boundary waters inrush calculation model constructed is shown in Figure 14.



**Figure 14.** Network-fit-boundary water diversion calculation model.

The flow of water in the gob of the upper coal seam in the attach waters inrush fracture is due to its characteristics of long action time and slow flow, so the water flow in the attach water inrush fracture belongs to Darcy flow, which can be approximately regarded as pore flow. In addition to the network water inrush fractures, boundary waters inrush fractures and attaching water inrush fractures, the interaction between inter-layer rock strata and water is not considered; only the interaction between water and inter-layer rock strata in attaching water inrush fractures is considered, while the interaction between water flows and inter-layer rock strata in network water inrush fractures and boundary water inrush fractures is negligible. The stress–strain relationship of the mechanical field of the inter-layer rock in the water area of the water inrush fracture is expressed by the statistical damage constitutive relation considering the water damage effect, as shown in Equation (17).

$$\sigma_1 = E\varepsilon_1 \times \exp\left[-\frac{F_{ms}}{\lambda}\right]^k \times D_w(t, w) + 2v\sigma_3. \quad (17)$$

The expression of the damage variable is:

$$\begin{cases} D_w(w, E_0) = \frac{\exp(2.787-5.38e-3 \times w - 1.87e-5 \times w^2)}{E_0} (0 < w < 100\%) \\ D_w(t, E_0) = \frac{\exp(3-0.22t+0.007t^2)}{E_0} (0 < D_w < 1) \end{cases}. \quad (18)$$

When water flows in the water inrush fracture, this process belongs to the pore flow state and conforms to the Darcy seepage theorem. The differential governing equation of pore flows can be expressed as (19) [35].

$$(k(\Theta, p)p, i), i = n \frac{\partial p}{\partial t} + \frac{\partial e}{\partial t} + W. \quad (19)$$

In the formula,  $p$  is the water pressure in the fracture;  $e$  is fracture volume deformation;  $W$  is water source;  $t$  is time;  $k$  is the fracture permeability coefficient.

$$k(\Theta, p) = \zeta_1 k_0 e^{-(\Theta/3-\beta p)}. \quad (20)$$

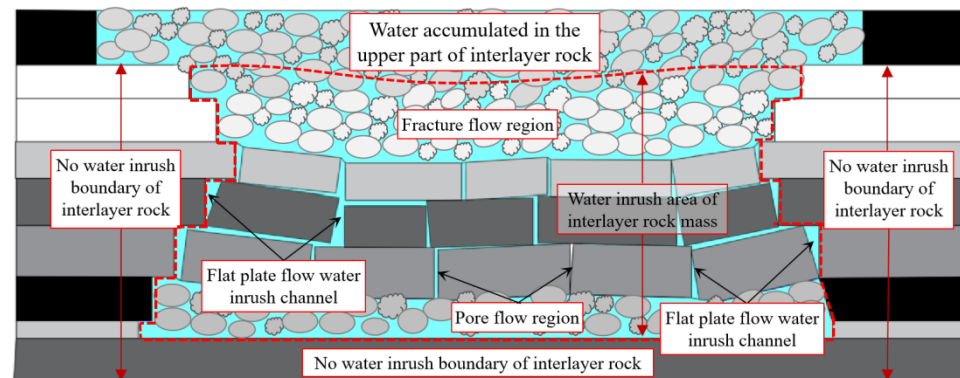
$\zeta_1 = 1.0$ ,  $\beta = 0.5$ ;  $\Theta$  is the volume stress,  $\Theta = \sigma_1 + \sigma_2 + \sigma_3$ ;  $e$  is the volume strain,  $e = \varepsilon_1 + \varepsilon_2 + \varepsilon_3$ .

In the network-attaching-boundary water inrush calculation model constructed, the flow of water accumulated in the upper part of the inter-layer rock in the network water inrush fracture and the boundary waters inrush fracture can be analyzed and calculated according to the part of the network-boundary water inrush calculation model. The water

flow in the network waters inrush fracture is the fracture flow pattern, which conforms to the non-Darcy seepage movement. The water flow in the boundary water inrush fracture is a flat flow state, and the Darcy-Weisbach equation is used to express the flow state of water in the boundary water inrush fracture through multiple inter-layered rock.

#### 4.1.3. Boundary Conditions and Initial Conditions of Water Inrush Area

The boundary conditions and initial conditions of the water flow field in the process of water inrush from the upper water accumulation in the inter-layer rock are studied, as shown in Figure 15.



**Figure 15.** Schematic diagram of the flow-solid coupled syncline boundary of an inter-layer rock.

The flow field area of water accumulation in the gob of the upper coal seam is mainly the rock between the lower layers of the gob; that is, the inter-layer broken rock within the red dotted line, the rock mass between the unbroken faults, and the lower coal seam floor is the boundary of no water inrush. The internal water flow field of the inter-layer rock is mainly the network water inrush fracture and the boundary water inrush fracture, followed by the water flow area in the water inrush fracture. When the water in the upper part of the inter-layer rock flows in the water inrush fracture, the water flows attaches to the water inrush fracture. When the upper water flows in the network water inrush fracture and the boundary water inrush fracture, the boundary condition of the upper water inrush in the inter-layer rock can be obtained without flowing in the inter-layer rock layer where the water inrush fracture is formed.

The height of the water head in gob after upper coal seam mining is:

$$h = h_z. \quad (21)$$

In the formula,  $h_z$  is the distance between the water surface of the gob and the inter-layer rock.

The hydro-static pressure in the gob is:

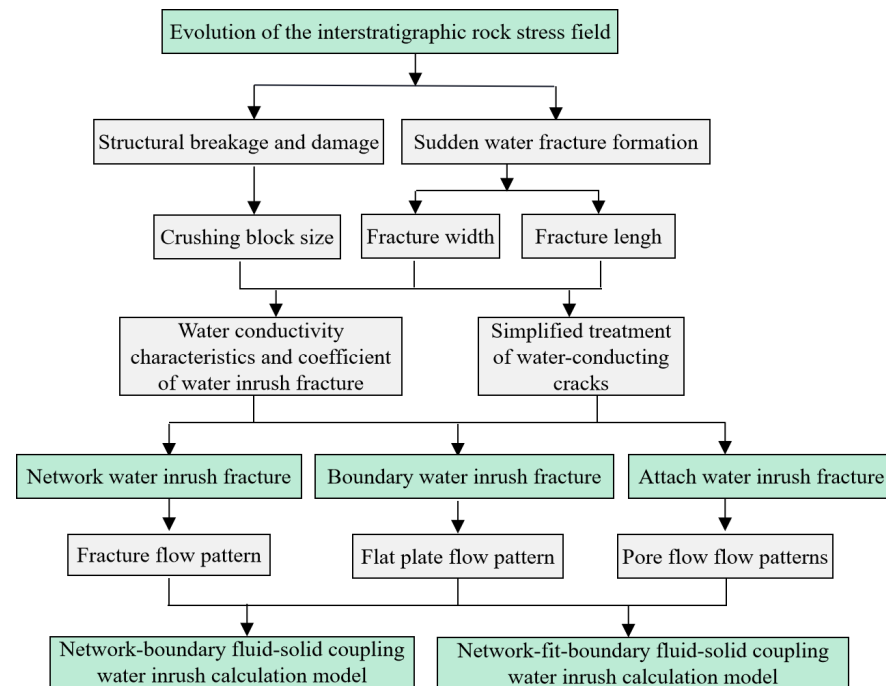
$$p_{gob} = 0. \quad (22)$$

### 5. The Initial Water Inrush Coefficient of Inter-Layer Rock Is: $K=K_0$

The boundary conditions of the stress field of the inter-layer rock are as follows: the boundary conditions of the stress field are the stress boundary conditions on both sides; that is, the sum of the self-generated gravity, the water load in the gob, and the gravity of the over strata multiplied by the lateral stress coefficient  $k_\sigma$  on both sides. The bottom of the inter-layer rock is the strain deformation boundary, the bottom is the fixed support condition, and the upper part of the inter-layer rock is the stress boundary condition, which bears the upper water load and the gravity of the overlying strata.

### 5.1. Solution of Fluid–Solid Coupling Model of Inter-Layer Rock

Based on the distribution characteristics of water inrush fractures and the classification of water inrush fractures, the fluid–solid coupling calculation models on the network-boundary water inrush calculation model and network-attach-boundary water inrush calculation model of inter-layer rock are constructed. When there are one or two force fields and water flow field control equations, multiple differential equations are more difficult in the calculation process. Through the analysis of the flow characteristics in the process of water inrush from inter-layer rock, the coupling relationship between water and inter-layer rock strata is not very close; only the water flow in the water inrush fracture is coupled with the inter-layer rock strata. Therefore, the idea of solving the flow process of water in inter-layer rock in this paper is as follows. The stress field and water-to-flow field are regarded as separate subsystems. According to the change in stress field and the change in water inrush coefficient, the change in different water inrush fractures in the damaged area of inter-layer rock is obtained, and the types of water inrush fractures are determined. Then, the calculation model of water inrush from inter-layer rock failure is determined. Finally, according to the plate flow state, fracture flow state, and pore flow state of water in the water inrush calculation model, the calculation is carried out. The specific solution idea is shown in Figure 16.



**Figure 16.** The flow chart of solving the water inrush model of inter-layer rock.

#### 5.1.1. Solution of Flat Plate Flows Water Inrush Model

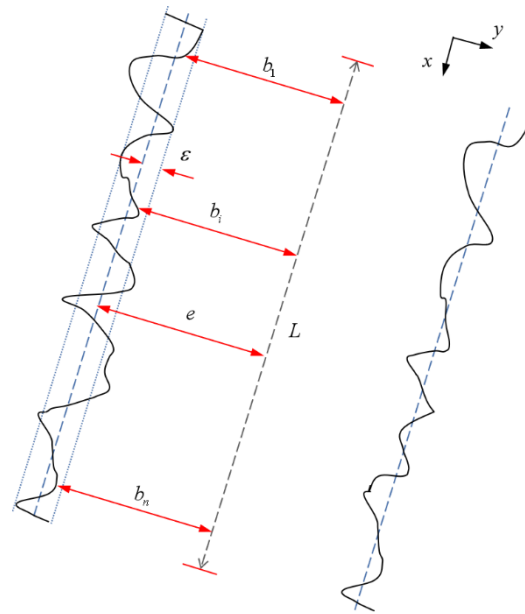
The unidirectional flow of incompressible fluid water in the boundary waters inrush fracture can be expressed by mass conservation and the N-S equation. The N-S equation includes fluid pressure, viscous force, body force, unsteady inertia force, and convective inertia force. It is generally believed that the flow of common fluid in the fracture is approximately steady motion. The body force is equivalent to the pressure on calculation, and the unsteady inertia force is neglected. The equation is simplified as:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \quad (23)$$

$$\rho \left( u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = -\frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right), \quad (24)$$

$$\rho \left( u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y} \right) = - \frac{\partial p}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right). \quad (25)$$

In the formula,  $u, v$  is the flow velocity of water in the  $x, y$  direction of the fracture;  $\mu$  is the viscosity of fluid water;  $\rho$  is the density of water;  $p$  is pressure. Taking the water-inrush fracture boundary in Figure 17, the fracture surface of the water-inrush fracture is a rough surface, so it is approximately regarded as symmetrical distribution; only half of the water-inrush fracture surface is discussed.



**Figure 17.** Part of the boundary water flowing fracture diagram.

In Figure 17,  $b_i$  is the distance from any point on the boundary water inrush fracture surface to the middle line of the fracture,  $i = 1, 2, 3, \dots, n$ . If the water inrush fracture width  $e$  can be regarded as the mean of all fracture widths, the roughness fluctuation of the water inrush fracture surface  $b_i$  is much smaller than the width of the water inrush fracture; that is,

$$b_i = e + o(b_1, b_2, \dots, b_n). \quad (26)$$

In the formula,  $o$  is the infinitesimal function of  $b_1, b_2, \dots, b_n$ , i.e.,  $o \ll e$ . If available,  $(b_i - e)|_n \ll e$ . If it is expressed by the roughness of the water inrush fracture surface,

$$\varepsilon = \max \left( \frac{\sigma_u}{e}, \frac{\sigma_1}{e} \right) \ll 1. \quad (27)$$

In the formula,  $\sigma_u, \sigma_1$  is the standard deviation of the rough fluctuation height  $b_i$  of the left and the surface of the water inrush fracture and its average  $e$ ;  $\varepsilon$  is the dimensionless roughness coefficient.

Based on the roughness of the water inrush fracture surface in Equation (27), the characteristic flow velocity of water in the  $x$  direction of the fracture surface is set as  $U$ , and the velocity  $v$  perpendicular to the water inrush fracture surface can be obtained from Equation (23):

$$v = - \int_0^y \frac{\partial u}{\partial x} dy. \quad (28)$$

Through the order of magnitude analysis, it can be seen that the order of magnitude of the flow velocity  $u$  in the  $x$  direction is  $U$  and the order of magnitude of the flow velocity  $v$  in the  $y$  direction is  $U \frac{e}{L}$ , so it is assumed that

$$\delta = \frac{e}{L} \ll 1. \quad (29)$$

The flow velocity  $v$  of water in the  $y$  direction of the boundary water inrush fracture is much smaller than the flow velocity  $u$  in the  $x$  direction; that is,  $v \ll u$ , so the flow velocity  $v$  in the  $y$  direction can be ignored. Equation (25) can be transformed into

$$\frac{\partial p}{\partial y} = 0, \text{ as } p = p(x). \quad (30)$$

Based on the ratio of inertial force and viscous force in the analysis Formula (25) of the N-S mass conservation equation, we have

$$\frac{|\text{inertia force}|}{|\text{cohesion}|} = \frac{\rho \left| u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right|}{\mu \left| \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right|} = \frac{\rho \left| u \frac{\partial u}{\partial x} \right|}{\mu \left| \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right|} \sim \frac{\rho}{\mu} \frac{U \frac{U}{L}}{\frac{U}{L^2} + \frac{U}{e^2}} = \frac{\rho U e}{\mu} \frac{\delta}{\delta^2 + 1} = \text{Re} \delta \quad (31)$$

where  $\text{Re}$  is the Reynolds coefficient. When water flows in the boundary water inrush fracture,  $\text{Re} = \rho U e / \mu$ . If Equation (30) meets the condition  $\text{Re} \delta \ll 1$ , the inertia force of water flow can be ignored, and Equation (25) can be transformed into

$$-\frac{\partial p}{\partial x} + \mu \frac{\partial^2 u}{\partial y^2} = 0. \quad (32)$$

The cubic law of water flow in the boundary water-inrush fracture can be obtained by integrating the cross-sectional area along the  $y$  direction of the boundary water-inrush fracture and combining the Formula (30):

$$q = \int_e u dy = -\frac{e^3}{12\mu} \frac{\partial p}{\partial x} = -\frac{e^3}{12\mu} \frac{\Delta p}{L}. \quad (33)$$

In the formula,  $\Delta p$  is the pressure difference at both ends of the boundary water inrush fracture.  $e$  is the distance from the flat approximate plate surface to the fracture center line.

The conditions of whether the water flow in the boundary water inrush fracture is suitable for the flat plate cubic law can be obtained by combining the Formula (27), Formula (29), and formula ( $\text{Re} \delta \ll 1$ ).

$$\begin{cases} \max(\varepsilon, \delta) \ll 1 \\ \text{Re} \delta \ll 1 \end{cases}. \quad (34)$$

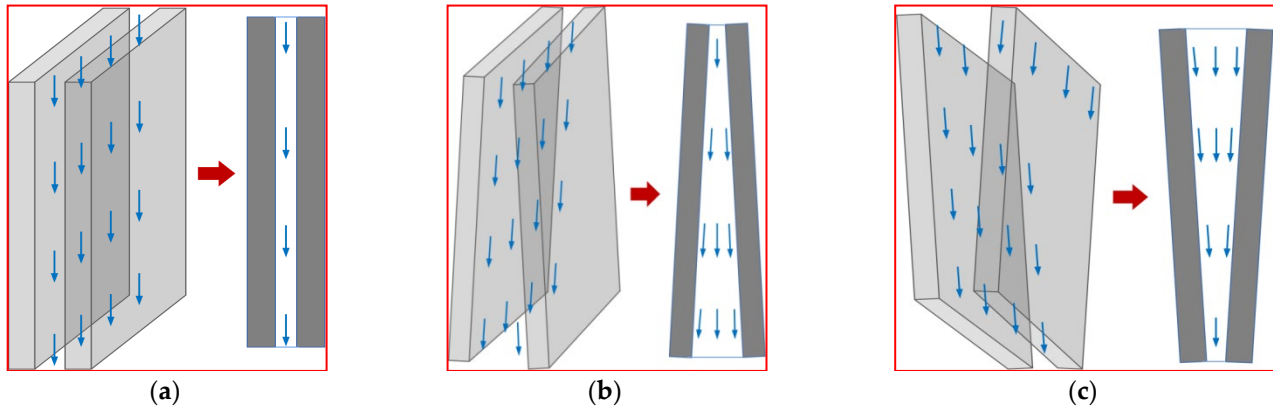
Based on the above analysis, according to the cubic law of plate flow in Formula (34), it can be seen that the Reynolds coefficient and the fracture roughness affect each other. When  $\delta$  is smaller, the cubic law is established under the higher Reynolds coefficient. Similarly, when the Reynolds coefficient is smaller, the cubic law has stronger adaptability in rough fractures. Therefore, for the smooth plate  $\varepsilon \equiv 0$ , the flow of the fracture is long enough; that is, the cubic law of  $\delta \rightarrow 0$  is fully established in the laminar flow range ( $\text{Re} \leq 2300$ ).

Based on the analysis of the similar simulation results from the distribution and evolution characteristics of the boundary water inrush fractures in the inter-layer rock, it can be seen that the boundary waters inrush fractures are affected by the mining of the upper and lower coal seams throughout the inter-layer rock, and the water accumulation in the upper coal seam gob is in the inter-layer rock boundary water inrush fractures. The flow rate is fast, and the water inflow is large. Therefore, based on the above comprehensive analysis, the boundary waters inrush fractures in the inter-layer rock in the three-dimensional space are regarded as flat fractures, and the flow of water in the gob in the boundary waters inrush fractures are regarded as a flat fracture flow water inrush model. As shown in Figure 18.

According to the cubic law of plate fracture flow, the velocity of water in the boundary water inrush fracture can be expressed as

$$u = -\frac{1}{2\mu} \frac{dp}{dx} \left[ y^2 - \left( \frac{b}{2} \right)^2 \right]. \quad (35)$$

In the formula,  $x$  is the direction of water flow;  $y$  is perpendicular to the direction of water inrush fracture surface;  $u$  is the velocity of water flow in  $x$  direction, m/s;  $b$  is the width of water inrush fracture, m;  $\mu$  is the dynamic viscosity of water,  $\text{Mpa} \cdot \text{s}$ ;  $dp/dx$  is the pressure gradient in the  $x$  direction,  $\text{Pa/m}$ .



**Figure 18.** Boundary water-conducting fracture plate-type water-conducting model. (a) ‘II’ type plate, (b) ‘Λ’ type plate, and (c) ‘V’ type plate.

It can be seen from Equation (35) that the velocity profile presents a parabolic surface when water flows in the plate fracture. The calculation formula for the fracture flow per unit cross-section length of the plate waters inrush fracture can be obtained by integrating Equation (23); therefore, the cubic law is

$$q = -\frac{b^3}{12\mu} \frac{dp}{dx}. \quad (36)$$

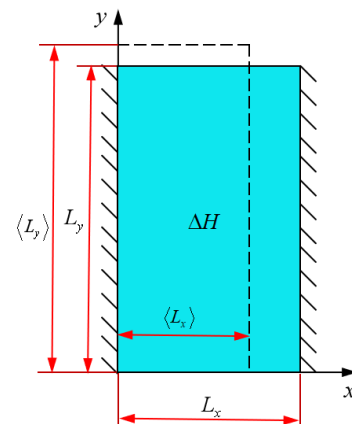
In order to solve the water flow in the fracture of the inter-layer rocks boundary more accurately, based on the parallel plate cubic law, the generalized cubic theorem is used to solve the water inrush model of the plate flow state under the influence of the roughness and opening degree of the plate composed of the rock strata between the broken faults. It is assumed that the area of the water inrush fracture on the plate is a rectangular plane of  $A = L_x L_y$ , and  $L_x$  and  $L_y$  are the length and width of the water inrush fracture plane, respectively. The upper and lower boundaries of the water inrush fracture plane are fixed head boundaries, the water head difference is  $\Delta H$ , and the left and right boundaries are impermeable boundaries. The plane flow model of rectangular water inrush fracture is shown in Figure 19. It is assumed that the average initial opening of the two planes of the water inrush fracture is  $b_0$ , and the initial area contact rate of the two planes is  $\zeta_0$ . Under the action of the fracture pressure and shear load of the inter-layer rock stratum, the water inrush fracture plane produces the normal total deformation  $u$  under the combined action of compression closure deformation and share opening deformation. The instantaneous mechanical opening is  $b$ , and the area contact rate is  $\zeta$ . In order to facilitate the subsequent solution, the normalized opening  $\bar{b} = b/b_0$  is defined.

The normal total deformation of the water inrush fracture plane is produced under the combined action of compression closure deformation and shear opening deformation, which can be expressed as

$$u = u_e + u_p = \frac{\sigma_n}{k_n} - \int_{\delta_0}^{\delta} \tan \psi d\delta_p. \quad (37)$$

In the formula,  $u$  is the total normal deformation of the fracture plane;  $u_e$  is the elastic component of the normal deformation of the fracture plane;  $u_p$  is the normal deformation plastic component of the fracture plane;  $k_n$  is the normal stiffness of the fracture plane. The first item on the right side of Formula (37) is the nonlinear elastic closure deformation

of water inrush fracture plane normal compression; the second term is the plane opening deformation caused by shear.



**Figure 19.** Plane flow model of rectangular water-conducting fracture.

During the break process of inter-layer rock, the contact area and the opening degree of the boundary water inrush fracture surface will change into the action of compression–shear load. When the normal compression deformation of the fracture surface occurs, the mechanical opening of the fracture surface decreases, and the contact area increases. When the shear expansion occurs on the fracture surface, the mechanical opening of the fracture surface increases and the area contact rates decreases. When the fracture surfaces reach a certain amount of closure of the action of normal load, the bulge formed by the fracture of the water inrush fracture surface will be flattened or crushed, and the area contact rate reaches a certain value and has nothing to do with the opening. Therefore, the evolution law of the area contact rate of the fracture plane under compression–shear loads is as follows.

$$\zeta = \zeta_{\infty} e^{-a\bar{b}}. \quad (38)$$

In the formula,  $\zeta$  is the area contact rate under the compression–shear action of the fracture surface;  $\zeta_{\infty}$  is the area contact rate when the fracture surface is closed;  $\bar{b}$  is the normalized opening of the structure;  $a$  is the fitting parameter. Under the initial conditions, the normalized opening  $\bar{b} = 1$  and the contact rate of the fracture surface are  $\zeta_0 = \zeta_{\infty} e^{-a}$ . If  $\zeta_0$  is known, then  $a$  computes  $a = -\ln(\zeta_0/\zeta_{\infty})$ . Obviously, when the water inrush fracture surface is completely closed,  $\zeta = \zeta_{\infty}$ ; when the compression deformation occurs on the water inrush fracture surface,  $\zeta > \zeta_0$ ; when the water inrush fracture surface occurs shear deformation,  $\zeta < \zeta_0$ . During the deformation process of the water inrush fracture surface, when the mechanical opening reaches a stable value, the contact rate of the fracture area also reaches a certain value. Equation (38) shows that the area contact rate and shear angle of water inrush fracture surface have the same variation law, and the area contact rate of the fracture surface is mainly controlled by shear characteristics.

When the area contact rate of the water inrush fracture surface is  $\zeta$ , the effective water inrush area does not exceed  $(1 - \zeta)A$ . Therefore, when the effective contact area of the fracture surface decreases, the effective flow width of the water inrush fracture surface decreases, resulting in the transformation of the groove to the pipe flow on the flat fracture surface to increase the water inrush diameter. It is assumed that the effective flow width of the water inrush fracture surface is reduced from  $L_x$  to  $\langle L_x \rangle$ , and the effective flow length is increased from  $L_y$  to  $\langle L_y \rangle$ , as shown in Figure 19. In order to define the equivalent hydraulic opening of water inrush fractures surface, there is

$$\langle L_x \rangle \langle L_y \rangle = A = L_x L_y. \quad (39)$$

Under the condition of considering the change in contact rate of water inrush fracture area, it is assumed that the decrease of effective flow width of water inrush fractures surface and the effective flow length had the same ratio, then

$$\langle L_x \rangle = (1 - \zeta)^{1/2} L_x = \left(1 - \zeta_\infty e^{-a\bar{b}}\right)^{1/2} L_x, \quad (40)$$

$$\langle L_y \rangle = (1 - \zeta)^{-1/2} L_y = \left(1 - \zeta_\infty e^{-a\bar{b}}\right)^{-1/2} L_y. \quad (41)$$

By introducing the equivalent hydraulic aperture  $\langle b \rangle$  of the water inrush fracture surface, the loss of water flows energy in the water inrush fracture surface can be well solved; that is, the water inrush fracture surface and the smooth, ideal water inrush fracture surface are lost, respectively. When considering the field water inrush fracture surface with mechanical opening  $b$ , effective flow width  $\langle L_x \rangle$ , and effective flow length  $\langle L_y \rangle$ , the flow diffusion energy of water inrush fracture surface can be expressed as Equation (42). When considering the water inrush fracture surface of the equivalent hydraulic opening  $\langle b \rangle$ , ideal flows width  $L_x$ , and ideal flows length  $L_y$ , the flow diffusion energy of the water inrush fracture surface can be expressed as Equation (43).

$$E = \int_{\langle L_y \rangle} \frac{gb^3}{12v} \left(\frac{dH}{dy}\right)^2 \langle L_x \rangle dy \approx \frac{gb^3}{12v} \frac{\Delta H^2}{\langle L_y \rangle} \langle L_x \rangle, \quad (42)$$

$$E = \int_{L_y} \frac{g\langle b \rangle^3}{12v} \left(\frac{dH}{dy}\right)^2 L_x dy \approx \frac{g\langle b \rangle^3}{12v} \frac{\Delta H^2}{L_y} L_x. \quad (43)$$

In the formula,  $E$  is the total energy of water flow and diffusion in the water inrush fracture surface.

According to the equivalent principle of water flow diffusion energy, the water flow energy of the field waters inrush fracture surface is equal to that of the smooth, ideal water inrush fracture surface. Combined with Formulas (40) and (41), the equivalent hydraulic opening of the water inrush fracture surface can be expressed as

$$\langle b \rangle = b(1 - \zeta)^{1/3} = b \left(1 - \zeta_\infty e^{-a\bar{b}}\right)^{1/3}. \quad (44)$$

Because it is impossible to reach complete waterless flow when the water inrush fracture surface is completely closed, the total flow of the water inrush fracture surface is

$$Q = Q_1 + Q_\infty. \quad (45)$$

In the formula,  $Q_1$  is the water flow related to the change in opening degree under the compression–shear load of water inrush fracture surface.

$$Q_1 = -\frac{g}{12v} \langle b \rangle^3 L_x \frac{\Delta H}{L_y}. \quad (46)$$

In Formulas (44) and (45),  $Q_\infty = -k_\infty b_0 L_x \frac{\Delta H}{L_y}$  is combined, in which  $k_\infty$  is the water inrush coefficient related to the lithology and fracture structure of the rock layer between the faults. Equation (46) can be converted to

$$Q = \beta Q_0. \quad (47)$$

In the formula,  $\beta$  is a dimensionless parameter;  $Q_0$  is the flow of water through a smooth plane with an opening degree of  $b_0$  and a water inrush coefficient of  $k_0$ .

$\beta$  can be expressed as

$$\beta = \bar{b}^3 \left(1 - \zeta_\infty e^{-a\bar{b}}\right) + k_\infty / k_0. \quad (48)$$

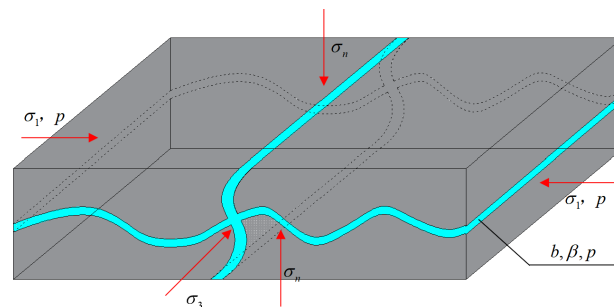
According to Equation (48), the dimensionless parameter  $\beta$  is related to the change in the opening degree of the water inrush fracture surface, the contact rate of the fracture

surface, and the ratio  $k_{\infty}/k_0$ . At that time,  $\bar{b} \rightarrow 0$  and  $\beta \rightarrow k_{\infty}/k_0$  indicate that the water inrush characteristics of the fracture surface after the fracture surface have a large closure; with the increase in  $\bar{b}$ ,  $\beta \rightarrow \bar{b}^3(1 - \zeta_{\infty}e^{-a\bar{b}})$  shows the water inrush characteristics under the coupling effect of shear expansion, profit softening, and the change in contact rate of fracture surface area. When  $\beta = 1$ , it represents the change in water inrush quantity of water inrush fracture on the smooth plate fracture surface without stress, with an initial contact area of zero and  $k_{\infty}$  tending to zero.

In summary, by solving the three-dimensional flat plate flow model and analyzing the rectangular planar model of the boundary water-inrush channel of the interlayer rock, it can be obtained that the water movement toward the boundary water-inrush channel can be completely transformed into the solution to the flat plate flow model mentioned above; by considering the roughness of the boundary water-inrush channel and the change in the width and length of the fractures, it can truly respond to the mechanism of the boundary water-inrush of the interlayer rock under the influence of the quarrying. This can also provide the theoretical basis for the control and prediction of water-inrush disasters.

### 5.1.2. Solution of Fracture Flow Water Inrush Model

For the solution of the fracture flow water model when the gob water flows in the network water inrush fractures of the inter-layer rock, only the coupling effect of the water flow field in the network water inrush fractures and the rock layer between the broken faults are considered; the pore flow inside the inter-layer rock layer is not considered. Therefore, the flow process of gob water in the network waters inrush fractures is different from the plate flow boundary water inrush fractures. The rock strata of the network water inrush fractures medium do not exist *REV* (rock mass characterization unit volume), or the scale *REV* is equivalent to the macroscopic engineering scale of the inter-layer rock strata fracture. Therefore, the research on the water inrush of this part of the inter-layer rock strata can only be solved by the research method of rock structure mechanics; that is, the whole inter-layer rock is regarded as composed of several matrix inter-layer rock blocks and network water inrush fracture structures. The water accumulation in the gob is solved in the form of fracture flow in the inter-layer rock strata. The three-dimensional stress inter-layer rock fracture flow model is shown in Figure 20.



**Figure 20.** Three-dimensional stress inter-layer rock fracture flow model.

In order to build the water inrush model research closer to the actual project site, the following assumptions are made for the construction model:

- ① The inter-layer rock of the network water inrush fracture part is a structure composed of the inter-layer broken rock layer, and the network water inrush fracture, the rock layer between the broken faults, is a homogeneous and isotropic elastomer.
- ② Compared with the network water inrush fractures, the water storage capacity and permeability of the rock strata between the broken faults are particularly weak, so the water storage capacity and permeability of the rock strata between the broken faults are not considered or ignored.
- ③ The flow of water in the network waters inrush fractures to obey Darcy's law  $q = -k_f \frac{\partial p}{\partial s}$ , where,  $k_f = -b^2/12$ .

- ④ The deformation law of network waters inrush fractures to obey the *Goodman* joint model.
- ⑤ The effective stress law of the network water inrush fracture is  $\sigma' = \sigma - p_f$ , and the rock layer between the fault is only affected by the solid stress.

The inter-layer rock is broken to form structural planes with different sizes and occurrences, inter-layer rock strata with different blocks and shapes divided by different structural planes. Therefore, the deformation of the fractured rock under external load depends on the deformation of the fractured rock block and the deformation of its structural plane. The deformation of the broken block of the inter-layer rock stratum is not considered; only the deformation of the structural plane is considered. Therefore, the deformation of the broken block of the inter-layer rock stratum adopts the stress–strain linear elastic relationship to elastic mechanics, and its elastic–plastic deformation is not considered.

Mathematic model of elastic deformation of inter-layer rocks fracture block. The deformation problem of rock strata between broken faults is analyzed. Firstly, an arbitrary parallel hexahedron is taken in the broken block of inter-layer rock strata. The parallel hexahedron is located in the rectangular coordinate system, and the position is the independent variable. The stress component is its function; the stress balance equation in tensor form is constructed based on the force and moment balance Equation (37).

$$\sigma_{ij,j} + f_i = 0. (i, j = 1, 2, 3). \quad (49)$$

Considering the geometric shape of the rock fracture block of the water inrush fractures, the relationship between the deformation component and the displacement can be derived, and the geometric equation in tensor forms is obtained [37].

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) (i, j = 1, 2, 3). \quad (50)$$

Considering the geometric shape of the fracture block of the water inrush fractures, the relationship between the stress variation component and the deformation component is determined. The generalized Hu's law can be used to obtain the constitutive equation:

$$\varepsilon_{i,j} = \frac{1+v}{E}\sigma_{ij} - \frac{v}{E}\delta_{ij}\Theta. (i, j = 1, 2, 3), \quad (51)$$

$$\sigma_{ij} = 2G\varepsilon_{ij} + 6\frac{KGv}{E}\delta_{ij}\theta. (i, j = 1, 2, 3), \quad (52)$$

$$\theta = \varepsilon_{ij}, \Theta = \frac{E}{1-2v}\theta, \quad (53)$$

$$K = \frac{E}{3(1-2v)}, G = \frac{E}{2(1+v)}. \quad (54)$$

In the formula,  $E$  is the elastic modulus of inter-layer rock, GPa;  $v$  is the Poisson's ratio of inter-layer rock;  $\theta$  is the volume strain;  $K$  is the bulk modulus of elasticity of the broken block, GPa;  $G$  is the shear elastic modulus of the fracture block, GPa;  $\delta_{ij}$  is Kroneker symbol:  $\delta_{ij} = \begin{cases} 1, i = j \\ 0, i \neq j \end{cases}$ .

Equations (51) and (52) are constitutive relations expressed by stress and strain, respectively. When the deformation of rock strata between faults is expressed by displacement component, Equations (50) and (52) are substituted for Equation (49), and the linear combination of displacement or the linear combination of the first derivative is used to express stress. Finally, the tensor form equilibrium equation expressed by the displacement component is obtained; that is, the deformation model of inter-layer rocks fracture block.

$$(\lambda + G)u_{j,ij} + Gu_{i,ij} + f_i = 0 (i, j = 1, 2, 3). \quad (55)$$

In the formula,  $\lambda = \frac{Ev}{(1+v)(1-2v)}$ .

It is assumed that the deformation of the strata between the broken faults and the spatial structure surface formed by the network waters inrush fractures is continuous during the deformation process. Based on the study of the interaction between water and soil saturation, Terzaghi proposed the famous effective stress principle. Under the action of three-dimensional stress, it can be expressed as

$$\sigma_{ij}' = \sigma_{ij} - p\delta_{ij}, \quad (56)$$

where  $\sigma_{ij}'$  is the effective stress tensor, MPa;  $\sigma_{ij}$  is the total stress tensor, MPa;  $p$  is pore pressure, MPa.

In [38], based on the research of Terzaghi, the effective stress law in three-dimensional case is proposed; that is,

$$\sigma_{ij}' = \sigma_{ij} - \beta p\delta_{ij} (0 < \beta < 1). \quad (57)$$

In the formula,  $\beta$  is the effective stress coefficient, also known as the Biot coefficient. It mainly depends on the volume stress, fracture connectivity, pore pressure, and volume model of inter-layer broken rock blocks.  $\beta$  is not a constant but a linear function composed of the volumetric force and the pore force of the fractured rock mass. When the volumetric stress increases, the effective stress coefficient decreases.

The effective stress equation of network water inrush fracture is

$$\begin{cases} \sigma_n' = \sigma_n - \beta p_f \\ \sigma_s' = \sigma_s \end{cases}. \quad (58)$$

Coefficient  $\beta$  reflects the contact condition of the structural plane of the water inrush fracture. When  $\beta = 0$ , the water inrush fracture surface is completely closed; when  $\beta = 1$ , the water inrush fracture surface has no contact.

The deformation characteristics of network water inrush fractures are mainly affected by the overburden load and horizontal extrusion stress during the mining process of the upper and lower working faces, which causes the contact state, roughness, strength, deformation, and filling state of the inter-layer rock fracture surface. It is assumed that the normal deformation of the water inrush fracture surface is elastic deformation; the fracture is closed when the normal stress increases, but it is less than the initial fracture opening. When the normal stress decreases, the fracture surface completely recovers deformation, and there are no changes in the plastic zone. Because the width of the water inrush fracture unit is small, it is assumed that the fracture deformation obeys the spatial eight-node Goodman model, so the deformation of the network water inrush fracture is actually plane deformation, which is controlled by both tangential stress and normal stress. The governing equation is

$$\begin{cases} \sigma_n' = k_n b, \varepsilon_n = \delta_n / b \\ \sigma_s' = k_s \varepsilon_s b, \varepsilon_s = \delta_s / b \end{cases}. \quad (59)$$

In the formula,  $\sigma_n'$  and  $\sigma_s'$  are the normal stress and tangential stress of the network water inrush fracture, MPa;  $k_n$  and  $k_s$  are the normal stiffness and tangential stiffness of the network water inrush fracture, MPa/mm;  $\varepsilon_n$  and  $\varepsilon_s$  are normal strain and tangential strain.

Fracture waters flow and stress coupling model. The fracture width of the network waters inrush fracture changes obviously under the action of normal stress, so the fracture width is used as an intermediate variable to construct the relationship between the fracture stress change and the water flow. Because the physical meaning of the width change in the rough fracture and the smooth fracture is different, the ideal fracture model with the same mechanical width and hydraulic width is constructed here. The specific ideal fracture hydraulic model fractures width is  $b$ , the fracture surface is smooth and extends outward, the fracture length is greater than the fracture width, the fracture is regarded as a local plate fracture, and the water flow law is

$$v = k_f J_f. \quad (60)$$

In the formula,  $v$  is the average velocity of water in the fracture, m/s;  $k_f$  is the water inrush coefficient, mD.

The flow of water in the network waters inrush fracture is laminar flow, so the water inrush coefficient is

$$k_f = \frac{gb^2}{12u}. \quad (61)$$

The unit width flow of water in water inrush fracture is

$$q = \frac{gb^3}{12u} J_f, \quad (62)$$

where  $g$  is the acceleration of gravity, kg/m<sup>3</sup>;  $u$  is the water year, MPa · s. In Equation (62), the flow rate  $q$  is proportional to the cubic of the fracture width  $b$ ; that is, the cubic law of fracture seepage.

Based on the cubic law of fracture seepage, Barton [38] improved the coupling model of fracture water flow and stress on the basis of experimental research and theoretical analysis.

$$K_n^0 = 0.02 \left( \frac{JCS}{b_m} \right) + 2JRC - 10, \quad (63)$$

$$b_m = \frac{JRC}{5} \left( 0.2 \frac{\sigma_c}{JCS} - 0.1 \right). \quad (64)$$

In the formula,  $\sigma_c$  is the uniaxial compressive strength of rock strata between broken faults, MPa;  $JRC$  is the roughness coefficient of network water inrush fracture surface;  $JCS$  is the compressive strength of the network water inrush fracture surface, MPa.

When the single water inrush fracture surface is taken as the research object, the normal stress is  $\sigma_n$ , the mechanical width of the fracture surface is  $b_m$ , and the elastic constants of the fracture are  $\lambda$  and  $G$ . Assuming that the width of the water inrush fracture in the inter-layer rock network is much smaller than the inter-layer rock scale, it is considered that  $\varepsilon_x = \varepsilon_y = 0$ ,  $\gamma_{xy} = \gamma_{yx} = 0$ ; its generalized Hooke's law can be written as

$$\begin{Bmatrix} d\sigma_n \\ d\tau_{xz} \\ d\tau_{zy} \end{Bmatrix} = \begin{bmatrix} \lambda + 2G & 0 & 0 \\ 0 & G & 0 \\ 0 & 0 & G \end{bmatrix} \begin{Bmatrix} d\varepsilon_x \\ d\varepsilon_{zx} \\ d\varepsilon_{zy} \end{Bmatrix}. \quad (65)$$

Suppose that the relative displacements in the direction  $x, y, z$  are  $\delta_x, \delta_y, \delta_z$  respectively, then the Expression (65) can be expressed as

$$\begin{Bmatrix} d\sigma_n \\ d\tau_{xz} \\ d\tau_{zy} \end{Bmatrix} = \begin{bmatrix} K_n & 0 & 0 \\ 0 & K_s & 0 \\ 0 & 0 & K_s \end{bmatrix} \begin{Bmatrix} dU_z \\ d\delta_x \\ d\delta_y \end{Bmatrix}. \quad (66)$$

Among,  $K_n = \frac{\lambda+2G}{b_m-U_z}$ ,  $K_s = \frac{G}{b_m-U_z}$ .

When the water inrush fracture only considers the normal stress, Equation (66) can be transformed into

$$d\sigma_n = (\lambda + 2G) \frac{dU}{b_m - U_z}. \quad (67)$$

The integral of Equation (67) can be obtained.

$$U_z = b_m \left( 1 - e^{\frac{\sigma_n}{\lambda+2G}} \right). \quad (68)$$

The instantaneous mechanical width of single network waters inrush fracture is

$$b^\sigma = b_m - U_z = b_m e^{\frac{\sigma_n}{\lambda+2G}}. \quad (69)$$

Substituting Equations (63), (64), and (69) into Equation (68), the deformation width of network waters inrush fractures under normal stress is obtained.

$$b^{\sigma} = \frac{JRC}{5} \left( 0.2 \frac{\sigma_c}{JCS} - 0.1 \right) e^{\frac{JRC}{5} \left( 0.2 \frac{\sigma_c}{JCS} - 0.1 \right) \left[ 0.02 \left( \frac{JCS}{\frac{JRC}{5} \left( 0.2 \frac{\sigma_c}{JCS} - 0.1 \right)} \right)^{+2JRC-10} \right]}. \quad (70)$$

Fracture water coupling water inrush model. The continuity equation of network waters inrush fracture is

$$\frac{\partial(\rho\phi_k)}{\partial t} + \frac{\partial}{\partial x} \left( k_f \frac{\partial p}{\partial x} \right) + W = 0, \quad (71)$$

$$\frac{\partial(\rho\phi_k)}{\partial t} + \frac{\partial}{\partial y} \left( k_f \frac{\partial p}{\partial y} \right) + W = 0, \quad (72)$$

where  $\rho$  is the density of water, kg/m<sup>3</sup>;  $\phi_k$  is the porosity of inter-layer rock, %;  $k_f$  is the water inrush rate of fracture, mD;  $W$  is the sink-source term.

$$\frac{\partial(\rho\phi_k)}{\partial t} = \rho \frac{\partial\phi_k}{\partial t} + \phi_k \frac{\partial\rho}{\partial t}. \quad (73)$$

Taking pressure as a variable of density  $\rho$  and porosity  $\phi_k$  of inter-layer rock, then Equation (73) can be transformed into

$$\rho \frac{\partial\phi_k}{\partial t} + \phi_k \frac{\partial\rho}{\partial t} = \rho \frac{\partial\phi_k}{\partial p} \frac{\partial p}{\partial t} + \phi_k \frac{\partial\rho}{\partial p} \frac{\partial p}{\partial t}. \quad (74)$$

Assuming the compressibility factor  $\chi_f = (1/\rho)(\partial\rho/\partial p)$  of the fluid, the above equation can be obtained.

$$\frac{\partial(\rho\phi_k)}{\partial t} = \rho \left( \phi_k \chi_f + \frac{\partial\phi_k}{\partial p} \right) \frac{\partial p}{\partial t} = \rho S \frac{\partial p}{\partial t}. \quad (75)$$

In formula (75),  $S$  is the water storage coefficient, which is generally considered to be caused by the change in inter-layer rock strata. Substituting Equation (75) into Equations (71) and (72), there is

$$\left. \begin{aligned} \rho S \frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \left( k_f \frac{\partial p}{\partial x} \right) + W &= 0 \\ \rho S \frac{\partial p}{\partial t} + \frac{\partial}{\partial y} \left( k_f \frac{\partial p}{\partial y} \right) + W &= 0 \end{aligned} \right\}. \quad (76)$$

Equation (76) is the fluid–solid coupling water inrush model of water inrush fracture and water formed by inter-layer rock fracture.

Based on the above coupling model of fracture deformation and stress of inter-layer rock, the fracture state model of water accumulation in the upper part of inter-layer rock in network water inrush fractures is obtained, and the equation of fracture flow water inrush model is solved.

$$\left. \begin{aligned} \text{water inrush model : } \rho S \frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \left( k_f \frac{\partial p}{\partial x} \right) + W &= 0 \\ \rho S \frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \left( k_f \frac{\partial p}{\partial x} \right) + W &= 0 \\ \text{Interlayer rock deformation model : } (\lambda + G)u_{j,ij} + Gu_{i,ij} + f_i &= 0 (i, j = 1, 2, 3) \\ \text{Water inrush fracture deformation model : } \begin{cases} \sigma_n' = k_n \varepsilon_n b, \varepsilon_n = \delta_n / b \\ \delta_s' = k_s \varepsilon_s b, \varepsilon_s = \delta_s / b \end{cases} \\ \text{Effective stress model : } \begin{cases} \sigma_n' = \sigma_n - \beta p_f \\ \sigma_s' = \sigma_s \end{cases} \\ \text{Water inrush rate equation : } k_f = \frac{\bar{b}^2}{12JRC^5} \end{aligned} \right\}. \quad (77)$$

Initial conditions: assuming that the initial pressure and effective pressure are  $p_0$  and  $\sigma_0$  respectively, the gob water and inter-layer rock density is  $\rho_1$  and  $\rho_s$ , respectively.

Boundary conditions: constant pressure or constant flow on the interface  $S$  of the inter-layer rock mass.

$$p|_S = p_0(x, t), \text{ or } Q = Q_0(x, t). \quad (78)$$

The boundary displacement is quantified as:

$$\vec{u} \Big|_s = \vec{u}_0(x, t). \quad (79)$$

According to the above solution conditions, the variables  $u$  and  $p$  of the above fluid–solid coupling model are solved. The key parameters such as water inrush velocity, flow rate, strain, and stress are further solved to solve the fracture flow water inrush model. According to the model built above, it can be embedded in the numerical simulation software Comsol Multiphysics to calculate the flow process and results of water in the network water inrush fracture and make full use of the advantages of numerical calculation software to reflect the water inrush process in the real inter-layer rock mass network water inrush fracture to the greatest extent.

Through the above analysis, combined with the interlayer rock network water-inrush fracture characteristics and the adoption of stress effects, in addition to the interlayer rock breakage block elastic deformation mathematical model, fracture water flow and stress coupling model, and fracture water coupling water-inrush model to optimize, as well as the more prominent on-site network water-inrush channel and constructed fracture flows solving model, a better description of the mechanism of the interlayer rock network water-inrush can be obtained.

#### 5.1.3. Solution of Water Inrush Model of Pore Fracture Flow Pattern

When the upper water flows in the water inrush fracture of the inter-layer rock, due to its long flow time and slow flow speed, there is both the flow in the transverse water inrush fracture and the flow in the longitudinal water inrush fracture, so the water inrush solution process of the pore fracture flow state can be solved according to the fracture network seepage theory. The water flow in the water inrush fractures formed by the inter-layer rock strata is regarded as the movement toward the “double medium” seepage channels composed of fractures and pores. It is considered that the water inrush in the fractures formed by the inter-layer rock strata is strong, and the permeability between the pores is weak. The fracture system and the pore system are regarded as continuous; the water exchange of the fracture system and the pore system is considered separately. It is proposed and solved. Model assumptions:

- ① On the basis of primary pores, the inter-layer rock fracture blocks are cut into rock blocks of different shapes and sizes by widely distributed water inrush fractures; the primary pores and fractures are evenly distributed in the rock strata between the broken faults, thus forming two overlapping continua. The water inrush capacity of inter-layer rock strata is much larger than that of pores; the water inrush capacity of pores in other parts of inter-layer rock strata is neglected. There are two fluid pressures at each point in the seepage field, namely pore pressure and fracture pressure. The seepage of fluid in the water inrush fracture shows the pressure difference and violent mass exchange between the two systems.
- ② According to the principle of dimensional analysis, the mass exchange of the two systems is derived as

$$Q_{pf} = \frac{\rho C K_f}{\mu} (p_1 - p_2). \quad (80)$$

In the formula,  $C$  is the characteristic coefficient of fractured rock mass which is proportional to the avoidance of rock blocks.  $\mu$  is the dynamic viscosity of water;  $\rho$  is fluid density;  $K_f$  is the fracture water inrush coefficient;  $p_1$  is the pore system water pressure;  $p_2$  is the water pressure of fracture system;  $Q_{pf}$  is the flow rate of pores to fractures per unit volume of fractured rock blocks in unit time.

- ③ Assuming that the fractured rock layer is still homogeneous and isotropic for fracture and pore media, both fracture flow and pore to flow to obey Darcy’s law, the constitutive equation of water flow is

$$q_1 = -\frac{K_1}{u} \text{grad} p_1, \quad (81)$$

$$q_2 = -\frac{K_2}{u} \text{grad} p_2. \quad (82)$$

In the formula,  $q$  is the flow velocity;  $K$  is permeability.

The mass conservation equation is

$$\frac{\partial(\Phi_1 \rho)}{\partial t} + \text{div}(\rho q_1) + Q_{pf} = 0, \quad (83)$$

$$\frac{\partial(\Phi_2 \rho)}{\partial t} + \text{div}(\rho q_2) + Q_{pf} = 0. \quad (84)$$

In the formula,  $\Phi$  is porosity.

Considering the compressibility of fluid and medium (broken rock and fracture), the method of compression coefficient can be used to deal with it. Suppose that the compression coefficient of water is

$$\beta = \frac{1}{\rho} \frac{d\rho}{dp}. \quad (85)$$

There is

$$\frac{d\rho}{dt} = \beta \rho \frac{\partial p}{\partial t}. \quad (86)$$

The compression coefficient of inter-layer rock is  $\alpha_1$ , the compression coefficient of water inrush fracture is  $\alpha_2$ . According to the principle of effective stress, the pressure acting on inter-layer rock and water inrush fracture is  $p_1 - p_2$  and  $-(p_1 - p_2)$ , respectively.

Substitution (84) is available.

$$\frac{\partial(\Phi_1 \rho)}{\partial t} = \frac{\partial \Phi_1}{\partial t} \rho + \Phi_1 \frac{\partial \rho}{\partial t} = \Phi_1 \beta \rho \frac{\partial p_1}{\partial t} + \rho \alpha_1 \left( \frac{\partial p_1}{\partial t} - \frac{\partial p_2}{\partial t} \right). \quad (87)$$

The Formulas (80)–(82) and (87) are brought into Formulas (83) and (84), respectively.

$$\frac{K_1}{u} \Delta p_1 = (\Phi_1 \beta + \alpha_1) \frac{\partial p_1}{\partial t} - \alpha_1 \frac{\partial p_2}{\partial t} + \frac{CK_1}{u} (p_1 - p_2), \quad (88)$$

$$\frac{K_2}{u} \Delta p_2 = (\Phi_2 \beta + \alpha_2) \frac{\partial p_2}{\partial t} - \alpha_1 \frac{\partial p_1}{\partial t} + \frac{CK_2}{u} (p_1 - p_2). \quad (89)$$

Equations (88) and (89) can also use the water storage coefficient  $A$  to represent the compression coefficient of inter-layer rock and water. Ignoring the compression effect of the pressure of the two medium systems on the inter-layer rock, there is

$$K_1 \Delta p_1 = S_{s1} \frac{\partial p_1}{\partial t} + \frac{CK_1}{u} (p_1 - p_2), \quad (90)$$

$$K_2 \Delta p_2 = S_{s2} \frac{\partial p_2}{\partial t} + \frac{CK_2}{u} (p_1 - p_2). \quad (91)$$

Although the Barenblantt-hole fracture water inrush model considers the flow difference between the fracture and the pore system, it assumes that the two are isotropic and homogeneous, which is quite different from the actual situation, especially the fracture system. Therefore, based on this improvement, the random distribution of water inrush fractures in the inter-layer rock strata is expressed as an ideal model of the same cuboid composed of orthogonal fracture network segmentation. It is assumed that the direction of water flows is parallel to the water inrush fractures in each direction, the water inrush fracture groups perpendicular to each principal axis are equally spaced, and the fracture width is constant, but the spacing and width of the water inrush fracture groups along each principal axis can be different, so a homogeneous anisotropic calculation model is formed

and the flow of water in the inter-layer rock layer is ignored. The model equation proposed as the basis of Equation (91) is

$$(\Phi_1\beta + \alpha_1) \frac{\partial p_1}{\partial t} + \frac{CK_1}{u}(p_1 - p_2) = 0, \quad (92)$$

$$\frac{K_x}{u} \frac{\partial^2 p_1}{\partial x^2} + \frac{K_y}{u} \frac{\partial^2 p_1}{\partial y^2} + \frac{K_z}{u} \frac{\partial^2 p_1}{\partial z^2} = (\Phi_2\beta + \alpha_2) \frac{\partial p_2}{\partial t} - \frac{CK_2}{u}(p_1 - p_2). \quad (93)$$

When the gob water flows in the inter-layer rock mass, Equations (92) and (93) can be simplified as

$$S_{s1} \frac{\partial p_1}{\partial t} + \frac{CK_1}{u}(p_1 - p_2) = 0, \quad (94)$$

$$K_x \frac{\partial^2 p_1}{\partial x^2} + K_y \frac{\partial^2 p_1}{\partial y^2} + K_z \frac{\partial^2 p_1}{\partial z^2} = S_{s1} \frac{\partial p_2}{\partial t} - CK_2(p_1 - p_2). \quad (95)$$

In order to more accurately describe the fracture of inter-layer rock mass and the flow of water in inter-layer rocks strata, considering the elastic effect of rock strata between broken faults, this paper puts forward a calculation model of the water flow field and pore fracture field formed by water accumulation in gob in the attach water inrush fracture and inter-layer rock strata. The model assumes that the flow space of water is in the attach water inrush fracture, the contact area between fracture and inter-layer rock strata, and the non-flow area. According to the conservation equation, the equation of gob water flowing in the above area is determined, and the flow equation under the following three special conditions is mainly considered.

At the intersection of water inrush fractures, the algebraic sum of water flow at the intersection of water inflow and outflow is zero.

$$\sum_{N_j} Q_i = 0, j = 1, 2, \dots, n. \quad (96)$$

In the formula,  $N_j$  is the total number of intersecting water inrush fractures in the rock strata between the  $j$  nodes.

The attach water inrush fracture divides the inter-layer rock layer into  $r$  blocks; the attach water inrush fracture of each inter-layer rock layer can be regarded as a closed polygonal loop, and the algebraic sum of the pressure difference in the two closed loops is zero.

$$\sum_{K_j} L_i I_i = 0, j = 1, 2, \dots, m. \quad (97)$$

In the formula,  $L_i$  is the length of the first  $i$  water inrush fracture loop;  $I_i$  is the pressure gradient of the  $i$  water inrush fracture circuit;  $K_j$  is the total number of basic units surrounding the  $j$  polygon.

The longitudinal joint waters inrush fractures divide the inter-layer rock strata into irregular basic units, and only one fracture in each unit forms a curved channel.

$$\sum_{S_j} L_i I_i = \Delta H, j = 1, 2, \dots, r. \quad (98)$$

In the formula,  $\Delta H$  is the total pressure difference from the inflow boundary of the outflow boundary,  $S_j$  is the total number of the basic units of the  $j$  polygon, and  $i$  is the code of the unit path.

Equations (96)–(98) are available.

$$\begin{cases} \sum_{N_j} Q_i = 0 \\ \sum_{K_j} Q_i = 0 \\ \sum_{S_j} L_i I_i = 0 \end{cases}. \quad (99)$$

There are  $n + m + r$  equations in the formula, which constitute the control equation of this model. In the calculation process, the loop pressures gradient and node flow are used as the basic variables, which increases the number of unknowns to be solved. If the node pressure  $p_i$  is used as the basic variable, the fracture unit diversion coefficient and the pressure gradient are used to represent the node flow, and any joint water inrush fracture unit  $k$  is studied. The node number of the two endpoints is  $i, j$ . The width of the fracture is  $b_k$ , the length is  $L_k$ , the porosity is  $\Phi_k$ , and  $\rho$  is the water density. The flow rate of the inter-layer rock stratum unit  $k$  is

$$q_k = -\frac{b_k^2}{12u}(p_i - p_j)/L_k. \quad (100)$$

The node with  $m$  fracture unit convergence is  $i$ , it is connected with another  $m$  node  $k_i$  through  $m$  units. The flow balance of node  $i$  is studied. Because the node itself does not have the ability to store water, according to the mass conservation equation, the algebraic sum of the total flow at the node is zero; that is,

$$\sum_{k=1}^m q_k = 0, \quad (101)$$

$$-\frac{\rho}{12u} \sum_{k=1}^m \frac{b_k^2(p_i - p_{ki})}{L_k} = 0. \quad (102)$$

In the formula,  $p_i$  denotes the water pressure of node  $i$ ;  $p_{ki}$  denotes the water pressure of another node in the  $k$  unit of the contact node  $i$ . If considering the performance of the stored water of each joint water inrush fracture unit, the node has a sink or source, expressed by  $W_i$ ; the above equation can be written as

$$\sum_{k=1}^m \left( \frac{\partial(\rho\Phi_k)}{\partial t} - \frac{\rho}{12u} b_k^2 \frac{p_i - p_{ki}}{L_k} \right) + W_i = 0. \quad (103)$$

All the nodes studied constitute  $n$  equations for solving the water head of  $n$  nodes; not only the storage capacity of fractures is considered, but also the flow control equation of the fracture network is directly expressed by node pressure. It is convenient to solve by modern calculation methods such as finite element method.

In summary, by analyzing the characteristics of the water-surge channels in the inter-layer rock, the boundary water-inrush fractures, network water-inrush fractures, and attach water-inrush fractures can be transformed into the optimized flat plate flow model, fracture flow model, and pore-fracture flow model for the solution, and the analysis of water-inrush mechanism in the inter-layer rock can be carried out through the analysis of the water movement in the water conduction channel in different flow modes, and the constructed coupled flow-consolidation model can realistically respond to the mechanism of the disaster caused by the water surge in the interlayer rock.

## 6. Conclusions

- (1) Based on the slip line theory and the 'three zones' theory, the concept of damage fragmentation depth is proposed, and the interlayer rock mass structure is classified based on the damage fragmentation depth. When  $L \leq h_m + H_{k2}'$ , the thickness of the interlayer rock mass is less than or equal to the depth of complete damage and fragmentation, and the completely broken interlayer rock mass is formed. When  $L > h_m + H_{k2}'$ , the thickness of the interlayer rock mass is greater than the depth of complete damage and fracture, and the fracture–fracture superimposed interlayer rock mass is formed. When  $L \geq h_m + H_{li2}'$ , the thickness of the interlayer rock mass is greater than the sum of the floor failure depth and the water inrush fracture zone, and the broken–broken–broken combined interlayer rock mass is formed. A new method of structural division of water inrush disaster caused by damage of rock mass be-

tween close coal seams is proposed, which provides a basis for the study of water inrush disaster.

- (2) With the mining of the upper and lower coal seam working faces, the evolution law of the water inrush channel of the rock mass between the close coal seams shows that the water-conducting channel, the network water-conducting channel, and the boundary water-conducting channel appear in turn. In the process of upper coal seam mining, the interlayer rock mass water inrush is mainly based on the joint water inrush channel. In the process of lower coal seam mining, the interlayer rock mass water inrush is mainly based on the network water inrush channel and the boundary water inrush channel. The network water inrush channel undergoes an increase–decrease–constant change process, and the boundary water inrush channel undergoes an increase and then tends to be stable. The overall two-dimensional distribution of the water inrush channel of the interlayer rock mass is a positive trapezoid, the boundary water inrush channel is distributed on the side of the open–off cut, the side of the stop line of the working face, and the cracks in the whole interlayer rock mass are developed. The network water inrush channel and the bonding water inrush channel are distributed in the middle position of the inter-layer rock mass. The network water inrush channel runs through multiple inter-layer rock layers, and the degree of fracture development is smaller than that of the boundary water inrush channel. The bonding water inrush channel only runs through the single inter-layer rock layer, and the degree of fracture development is the smallest. The dynamic evolution process and distribution characteristics of water inrush channels in different inter-layer rock masses with the mining of working faces are revealed. Based on the evolution and distribution characteristics of water inrush channels, the water inrush process is transformed from qualitative analysis to quantitative research.
- (3) Combined with the characteristics of the water inrush channel in the inter-layer rock mass, the boundary water inrush crack has the characteristics of instantaneity and large water inflow. The network water inrush crack has the characteristics of horizontal and vertical flow equivalence. The joint water inrush crack has the characteristics of long action time and slow flow. Therefore, the boundary water inrush crack, the network water inrush crack, and the water movement in the joint water inrush crack are equivalently transformed into the flat plate flow state, the crack flow state, and the pore flow state movement, and the network-boundary, network-joint-boundary water inrush flow solid coupling calculation model is constructed. The fluid–solid coupling calculation model covers a variety of situations of water inrush from rock mass between close coal seams. Through the study of the characteristics and evolution law of the water inrush channel, the mechanism of water inrush from rock mass between different layers of close coal seams is revealed, and the research method of water inrush disaster mechanism and the application of water flow state transformation theory of different water inrush channels are expanded.

**Author Contributions:** Conduct on-site research on J.W., J.Z., T.Y., S.G. and Y.H.; manuscript writing, J.W.; similar simulation experiments Y.H., J.W. and S.G.; writing—review and correction, J.Z.; Methodology, S.Y. All authors have read and agreed to the published version of the manuscript.

**Funding:** This study was supported by the National Natural Science Foundation of China project (51774229, 52004200, 52004204), the order of sponsors is Jie Zhang, Tao Yang, Sen Yang. Thank you very much for the support of the National Natural Science Foundation project.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The relevant data of this manuscript were obtained from field measurement and tests, which are real and effective.

**Conflicts of Interest:** The authors declare that there are no conflict of interest in the publication of this paper.

## References

1. Qiao, W.; Wang, Z.; Li, W.P.; Lv, Y.G.; Li, L.G.; Huang, Y.; He, J.H.; Li, X.Q.; Zhao, S.L.; Liu, M.N. Formation mechanism, disaster-causing mechanism and prevention technology of roof bed separation water disaster in coal mines. *J. China Coal Soc.* **2021**, *46*, 507–522.
2. Wu, Q.; Cui, F.-P.; Zhao, S.-Q.; Liu, S.-J.; Ceng, Y.-F.; Gu, Y.-W. Type classification and main characteristics of mine water disasters. *Coal J.* **2013**, *38*, 561–565.
3. Qiao, W.; Li, W.P.; Sun, R.H.; Li, X.Q.; Hu, F. Formation mechanism of dynamic impact failure zone of super dynamic water inrush in coal mine. *Geotech. Eng.* **2011**, *33*, 1726–1733.
4. Li, X.Q. Study on the Inrush Mechanism of the Water in Bed Separation due to Repeated Coal Mining under Hard Rock. Master's Thesis, China University of Mining and Technology, Beijing, China, 2011.
5. Li, W.; Li, X.; Sun, R. Preliminary study on dynamic water inrush of coal mining under super-thick hard rock. *J. Eng. Geol.* **2008**, *16*, 446–450.
6. Xu, J.; Zhou, Y.; Pu, Z.; Pang, S. Calculation method of separated water accumulation and in the process of separated water inrush and its forecast: Taking the water inrush at 1304 working face of Zhaoxian Coal Mine in Shaanxi Province as an example. *J. China Coal Soc.* **2022**, *47*, 3083–3090.
7. Wang, Z. Experimental Study on Mechanism of Water Inrush with Mud and Sands from Roof Separation Layers in No.1 Coal Mine of Xinshanghai. Master's Thesis, China University of Mining and Technology, Xuzhou, China, 2022.
8. Qian, W.; Zhao, S.; Li, L. Study on evolution features of high level overburden separation layer and precursor information of water inrush during coal mining. *Coal Sci. Technol.* **2021**, *49*, 194–205.
9. Li, D.; Liu, S.Y.; Zhang, G.D.; Xu, H.J.; Zhao, B.F. Typical roof water disasters and its prevention & control technology in the north of Ordos Basin. *J. China Coal Soc.* **2017**, *42*, 3249–3254.
10. Lin, Q.; Qiao, W. Water prevention and control technology of roof bed separation in Cuimu Mine. *Coal Sci. Technol.* **2016**, *44*, 129–134.
11. Huang, Q.; Zhang, W.; Hou, Z. Study of simulation material of aquifuge for solid-liquid coupling. *J. Rock Mech. Eng.* **2010**, *29*, 2813–2818.
12. Qiao, W.; Huang, Y.; Yuan, Z.B.; Guo, W.; Zhou, D. Formation and prevention of water inrush from roof bed separation with fully-mechanized caving mining of ultra thick coal seam. *Chin. J. Rock Mech. Eng.* **2014**, *33*, 2076–2084.
13. Cao, D. Hydrostatic water inrush from bed separation and its prevention. *Hydro-Geol. Eng. Geol.* **2013**, *40*, 9–12+41.
14. Lv, Y.; Zhao, R.; Peng, T. A typical case analysis of water-sand inrush in mining under thick over-burden rock in Jurassic coalfield. *J. China Coal Soc.* **2020**, *45*, 3903–3913.
15. Lv, Y.; Xiao, Q.; Cheng, J. Mechanism and prevention of water-sand inrush in soft rock with weakly abundant water: A case study in Shanghai temple mining area. *J. China Coal Soc.* **2019**, *44*, 3154–3163.
16. Cao, H. Study on the Disaster Mechanism and Prevention and Control Technology of Overlying Strata Separation Water Body in Coal Seam Mining. Ph.D. Thesis, General Institute of Coal Science Research, Beijing, China, 2018.
17. Hebblewhite, B.K. Fracturing caving propagation and influence of mining on groundwater above long-wall panels—A review of predictive models. *Int. J. Min. Sci. Technol.* **2020**, *30*, 49–54. [\[CrossRef\]](#)
18. Li, L.; Shu, Z.; Feng, Y. Analysis and prevention on mechanism of water inrush from bed separation water of overburden by fully-mechanized top coal caving mining in ultra thick seam. *Coal Sci. Technol.* **2018**, *46*, 175–182. [\[CrossRef\]](#)
19. Gao, Y.F.; Huang, W.P.; Liu, G.L.; Zhang, S.F.; Zhu, Q.M.; Deng, Z.Y. The relationship between water permeable fractured zone and rock stratum tensile formation. *J. Min. Saf. Eng.* **2012**, *29*, 301–306.
20. Zhao, C.; Song, W. Mechanical Models for Comparative Analysis of Failure Characteristics and Groundwater Inrush of Coal Seam Floors. *Appl. Sci.* **2022**, *12*, 12164. [\[CrossRef\]](#)
21. Zhang, J.; He, Y.; Yang, T.; Bai, W.; Gao, S.; Yan, Y. Study on the Co-Evolution Mechanism of Key Strata and Mining Fissure in Shallow Coal Seam Mining. *Appl. Sci.* **2023**, *13*, 8036. [\[CrossRef\]](#)
22. Yang, H.; Bian, K.; Wang, T.; Jin, Z.; Liu, B.; Sun, H.; Chang, J. Risk Assessment and Water Inrush Mechanism Study of Through-Type Fault Zone Based on Grey Correlation Degree. *Appl. Sci.* **2023**, *13*, 6828. [\[CrossRef\]](#)
23. Smoliński, A.; Malashkevych, D.; Petlovanyi, M.; Rysbekov, K.; Lozynskyi, V.; Sai, K. Research into Impact of Leaving Waste Rocks in the Mined-Out Space on the Geomechanical State of the Rock Mass Surrounding the Longwall Face. *Energies* **2022**, *15*, 9522. [\[CrossRef\]](#)
24. Malashkevych, D.; Petlovanyi, M.; Sai, K.; Zubko, S. Research into the coal quality with a new selective mining technology of the waste rock accumulation in the mined-out area. *Min. Miner. Depos.* **2022**, *16*, 103–114. [\[CrossRef\]](#)
25. Wang, X.; Zhu, W.; Xu, J.; Han, H.; Fu, X. Mechanism of Overlying Strata Structure Instability during Mining below Unconsolidated Confined Aquifer and Disaster Prevention. *Appl. Sci.* **2021**, *11*, 1778. [\[CrossRef\]](#)
26. Liu, W.; Zhao, J.; Nie, R.; Zeng, Y.; Xu, B.; Sun, X. A Full Coupled Thermal–Hydraulic–Chemical Model for Heterogeneity Rock Damage and Its Application in Predicting Water Inrush. *Appl. Sci.* **2019**, *9*, 2195. [\[CrossRef\]](#)

27. Gao, X.; Liu, S.; Ma, T.; Zhao, C.; Zhang, X.; Xia, H.; Yin, J. A Prediction Method for Height of Water Flowing Fractured Zone Based on Sparrow Search Algorithm–Elman Neural Network in Northwest Mining Area. *Appl. Sci.* **2023**, *13*, 1162. [[CrossRef](#)]
28. Huang, M.; Yao, X.; Tan, Z.; Li, J. Research on Water Pressure Distribution Characteristics and Lining Safety Evaluation of Deep Shaft in Water-Rich, Large, Fractured Granite Stratum. *Appl. Sci.* **2022**, *12*, 7415. [[CrossRef](#)]
29. Zhang, S.; Guo, W.; Li, Y. Experimental simulation of water-inrush disaster from the floor of mine and its mechanism investigation. *Arab. J. Geosci.* **2017**, *10*, 503. [[CrossRef](#)]
30. Wu, M.; Ye, Y.; Hu, N.; Wang, Q.; Tan, W. Visualization analysis and progress of mine water inrush disaster-related research. *Mine Water Environ.* **2022**, *41*, 599–613. [[CrossRef](#)]
31. Ma, D.; Duan, H.; Zhang, J.; Bai, H. A state-of-the-art review on rock seepage mechanism of water inrush disaster in coal mines. *Int. J. Coal Sci. Technol.* **2022**, *9*, 50. [[CrossRef](#)]
32. Wang, X.; Xu, Z.; Sun, Y.; Zheng, J.; Zhang, C.; Duan, Z. Construction of multi-factor identification model for real-time monitoring and early warning of mine water inrush. *Int. J. Min. Sci. Technol.* **2021**, *31*, 853–866. [[CrossRef](#)]
33. Zhang, S.; Shen, B.; Li, Y.; Zhou, S. Modeling rock fracture propagation and water inrush mechanisms in underground coal mine. *Geofluids* **2019**, *2019*, 1796965. [[CrossRef](#)]
34. Li, L.-P.; Li, S.-C.; Shi, S.-S. Multi-field coupling mechanism of seepage damage for the water inrush channel formation process of coal mine. *J. Min. Saf. Eng.* **2012**, *29*, 232.
35. Zhao, Y. *Multi-Field Coupling of Porous Media and Its Engineering Response*; Science Press: Beijing, China, 2010.
36. Wu, L.; Bai, H.; Yuan, C.; Wu, G.; Xu, C.; Du, Y. A Water-Rock Coupled Model for Fault Water Inrush: A Case Study in Xiaochang Coal Mine, China. *Adv. Civ. Eng.* **2019**, *2019*, 9363917. [[CrossRef](#)]
37. Xue, S. *Elasticity*; China Building Materials Industry Press: Beijing, China, 2005.
38. Bandis, S.E.; Lumsden, A.C.; Barton, N.R. Fundamentals of rock joint deformation. *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.* **1983**, *20*, 249–268. [[CrossRef](#)]

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