Characteristics of Collapse Accumulation Body in Roadway and Numerical Simulation of Rescue Channel Excavation

Guangbo Chen
Inner Mongolia University of Science and Technology
Pengcheng Teng
Inner Mongolia University of Science and Technology
Huiqiang Duan
Inner Mongolia University of Science and Technology
Guohua Zhang
Heilongjiang University of Science and Technology
Tan Li (litan597@163.com)
Inner Mongolia University of Science and Technology

Research Article

Keywords: post-disaster rescue, fault fracture zone, accumulation body, characteristics, rescue tunnel, numerical simulation

Posted Date: June 1st, 2021

DOI: https://doi.org/10.21203/rs.3.rs-549397/v1

Version of Record: A version of this preprint was published at Geotechnical and Geological Engineering on July 22nd, 2021. See the published version at https://doi.org/10.1007/s10706-021-01946-1.

Characteristics of Collapse Accumulation Body in Roadway and Numerical Simulation of Rescue Channel Excavation

Guangbo Chen[1,2], Pengcheng Teng[1], Huiqiang Duan[1], Guohua Zhang[3], Tan Li[1*]

1. Institute of Mining and Coal, Inner Mongolia University of Science and Technology, Baotou 014010,China;
2. College of Energy and Mining Engineering, Shandong University of Science and Technology, Qingdao 266590,China;
3. School of Mining Engineering, Heilongjiang University of Science and Technology, Harbin 150022,China

*The full correspondence details for the corresponding author is as follows:

Tan Li

Address: Institute of Mining and Coal, Inner Mongolia University of Science and Technology, Baotou, Inner Mongolia 014010 China;

E-mail: litan597@163.com

Characteristics of Collapse Accumulation Body in Roadway and Numerical Simulation of Rescue Channel Excavation

Abstract: After the coal mine disaster, the collapsed accumulation body blocked the roadway and interrupted the rescue route, which seriously affected the development of rescue. Based on the post-disaster blockage rescue route of the collapsed accumulation body, the morphology and structural characteristics of the accumulation body were analyzed, and the process of excavating the rescue channel in the collapsed accumulation body in the mining roadway was simulated using CDEM software, and the moving mode of accumulation body fragments was discussed. The study found that: the formation of the accumulation body is the process of continuous "self-organization" adjustment of the rock fragments; the accumulation body along the direction of the roadway axis is divided into three areas: pre-sorting accumulation area, post-sorting accumulation area, and non-sorting accumulation area; the particle size of the accumulation body-particle content conforms to the normal distribution; the harder the rock fragments constituting the accumulation body is, the particle size of the fragments is more different; the number of contact points of the fragments of the tightly accumulation body is more than that of the loose accumulation body; the excavation of the rescue channel is accompanied by the random "self-organization" movement of the accumulated body; the settlement and deformation of the accumulated body is actually the continuous collapse of the old arch structure , and the process of continuous formation of a new arch structure; the initial force of the rescue channel excavation is small, then it increases sharply, and finally stabilizes; the fragment adjustment forms are mainly divided into horizontal movement adjustment, vertical movement adjustment, rotation movement adjustment, and multi-directional movement adjustment. The research conclusion has certain guiding significance for the rescue channel excavation under the condition that the collapsed accumulation body blocks the roadway after the coal mine disaster.

Key words: post-disaster rescue; fault fracture zone; accumulation body; characteristics; rescue tunnel; numerical simulation

0 Introduction

In recent years, coal resources have gradually entered the stage of deep mining, mine pressure has increased sharply, and geological conditions have become more complex, which has caused a series of disasters such(Cheng et al., 2016; Chen et al., 2020; Qin et al., 2019). After a disaster occurs, the action of strong impact and destructive force often causes roadway damage, collapse and blockage. This not only hinders the timely evacuation of disaster victims, but also delays the arrival of rescuers to the waiting area, which causes a sharp increase in the number of casualties. According to coal mine accident statistics, less than 10% of the people who die instantly at the primary scene of a major underground disaster(Qin et al., 2018; Gao and Wu, 2011; Xia et al., 2016; Yan et al., 2018). Therefore, how to effectively carry out post-disaster rescue has become an urgent problem to be solved(Zhang et al., 2012; Chen et al., 2019; Sun and Qian, 2017).

Many experts and scholars have carried out a series of studies on the collapse of roadways in coal mines after the disaster. Among them, Literature (Hao et al., 2013; Wang et al., 2011) analyzed the determinant conditions and influencing factors of the roadway collapse and blockage under the condition of the development of roof joints and cracks. Literature (Zhang et al., 2014; Bai et al., 2015) analyzed the collapse state of compound roof, and proposed rescue engineering recommendations from the perspective of post-disaster rescue according to different roof conditions. Literature (Hao et al., 2016) analyzed the collapse characteristics of the fault fracture zone after the gas explosion disaster, and provided theoretical and technical support for predicting the type of roadway collapse before implementing the rescue, the rescue time effect, and formulating the rescue plan. Literature (Zhang et al., 2017; Wu et al., 2012) gave the preferred location and shape of the rescue channel through numerical simulation. Literature (Pu et al., 2017) elaborated on the blockage characteristics of the slope-changing roadway in the disaster area, and constructed the physical model and mechanical model of the slope-changing roadway in the disaster area. Literature (Guo and Chen, 2016; Sun et al., 2015) carried out a numerical simulation on the overlying rock strata of the mining roadway, and discussed the mechanical relationship between the internal blocks of the collapsed accumulation body of the roadway. In literature (Zhang et al., 2018; He et al., 2019), a theoretical calculation formula for boundary forces is given and experimentally verified in response to the problem of force distribution on the boundary of accumulation body, which inevitably occurred in the decision-making research on safe and rapid excavation of rescue channels.

During the rescue process, it is inevitable that the roadway will be blocked by the accumulation body of the fault fracture zone. How to quickly excavate the rescue channel in the accumulation body to reach the waiting area is particularly critical. If rescue channels in the accumulation body is quickly excavated, the shape and structural characteristics of the collapsed accumulation body of the roadway must be first grasped. Although the above-mentioned experts have conducted relevant studies from the perspectives of the location and shape of the rescue channel, the mechanical relationship between the blocks in the accumulation body, etc., but the shape and structural characteristics of the collapsed accumulation body and the mechanical relationship between the accumulation body and the channel during the excavation of the rescue channel need to be studied in depth.

Based on this, the author analyzed the morphology and structural characteristics of the accumulation body after the disaster, and used CDEM software to simulate the process of excavating the rescue channel in the mining roadway, which provides coal mines with technical support for post-disaster emergency rescue under these conditions.

1 Characteristics of Collapsed Accumulation Body

1.1 Accumulation Characteristics of Collapsed Accumulation Body

In order to analyze the characteristics of the collapsed accumulation body, the situation of the collapsed deposits blocking the roadway of a coal mine in Heilongjiang Longmei Mining Group was investigated on site, as shown in Fig 1.

[**Fig 1** is about here]

It can be seen from Fig 1:

1) The accumulation body basically blocks the entire roadway, mainly concentrating on one side of the roadway. The rock blocks are relatively loose, with poor cementation between the blocks. The size of the fragments of the accumulation body is different, which is approximately “round”.

2) The accumulation process of the collapsed body shows a certain degree of sorting. In the sorting area, the particle size of rock masses gradually decreases from top to bottom. This sorting is due to the restriction of the both sides of roadway, and its direction is along the roadway axis. The accumulation body is divided into three areas along the axis of the roadway, namely the pre-sorting accumulation area, post-sorting accumulation area, non-sorting accumulation area, as shown in Fig 2.

[**Fig 2** is about here]

3) The accumulation body formed by the roadway collapse is composed of large-diameter blocks and particles. The

block particle size is between 10mm and 1000mm, and the larger particle size can reach 2000mm. The size, shape, and stacking methods of the accumulation body are all different. The appearance morphology and surface characteristics of the accumulated body have a certain impact on the number of contact points per unit volume, the contact area, and the size of the surface area of the contact position.

4) According to the field investigation, it is found that the accumulation method of the accumulation body particles can be divided into two types, one is the regular arrangement and the other is the random arrangement. In the three-dimensional space, if a hexahedron is used to represent the particles of the accumulation body, the contact methods are: edge-edge contact, corner-surface contact, surface-surface contact and edge-surface contact. If a sphere is used to represent the particles of the accumulation body, the contact methods are: cubic arrangement, oblique arrangement and dense arrangement, as shown in Fig 3.

[**Fig 3** is about here]

1.2 The Distribution Characteristics of the Collapsed Accumulation Body Particle Size

Tab 1 shows the survey data of coal, gritstone, and fine sandstone accumulation body. Fig 4 shows the particle size-content histogram of the accumulation body. From this the particle size distribution of the accumulation body can be seen:

Coal, gritstone, and fine sandstone have the smallest proportions of particles with two grades of <0.1mm and 800~1000mm. The proportions of particles of 4~5mm, 5~10mm and 10~20mm in coal accumulation bodies are larger, gritstone accumulation body with 5-10mm, 10-20mm, 20-50mm particles account for a larger proportion, fine sandstone accumulation bodies with 10-20mm, 20-50mm, 50-100mm particles account for a larger proportion. Particles with smaller and larger particle sizes in the accumulation body have a smaller proportion, while particles with a particle size of 4 to 5 mm, 5 to 10 mm, 10 to 20 mm, 20 to 50 mm, and 50 to 100 mm have a larger proportion. Coal has a higher degree of fragmentation and is prone to produce smaller fragments, while fine sandstone is less fragmented and prone to produce larger fragments. In engineering practice, there are many small fragments in the accumulation body formed by the collapse of the coal roadway, and the stability of the accumulation body is poor. The rescue channel support should be strengthened during the excavation process. The accumulation body formed by the collapse of the rock roadway is prone to large fragments. Large fragments can be crushed when it is necessary, or large fragments can be avoided when the rescue channel is excavated.

[**Tab 1** is about here]

[**Fig 4** is about here]

1.3 Characteristics of Logarithm-Content Curve of Collapsed Accumulation Body

Fig 5 is the logarithm of the particle size-content curve of the accumulation body. From this figure, it can be seen that the logarithm of the particle size-particle content distribution curve is a “bell-shaped” curve, and the particle size distribution of the accumulation body obeys the lognormal distribution law. In addition, the curve of coal accumulation body is steeper and the peak point is higher; the curve of fine sandstone accumulation body is slower and the peak point is lower; the curve of gritstone accumulation body is located between the above two. The harder the rock is, the slower the accumulation curve is and the more different the size of fragments is; the softer the rock is, the steeper the accumulation curve is and the more identical the size of the fragments is.

[**Fig 5** is about here]

1.4 Contact characteristic test of accumulation body particle

According to the accumulation state, the accumulation body can be divided into loose accumulation and tight accumulation. Fig 6 shows the accumulation morphology of the two accumulations. It can be seen from the figure that the shapes of the fragments of the two types of accumulations are extremely irregular. The fragments of the loose accumulation have sharp edges and corners, and the fragments of the tight accumulation are round; The difference of particle size of loose accumulation is larger, but that of tight accumulation is smaller; the fragments are arranged randomly, showing a certain disorder. The number and direction of contact points in the accumulation body are uncertain due to its morphological characteristics.

[**Fig 6** is about here]

In order to determine the number of contact points of the accumulation body fragments, an experiment was carried out to determine the number of accumulation body contact points. Place the two types of samples in a cylindrical container. The fragments will accumulate naturally. Use paint to soak the sample, drain the remaining paint, and let the sample air dry for 48 hours. Observe and record the number of contact points of the fragments. Do the same experiment five times for each type of sample.

It can be seen from Fig 7 and Fig 8 that the number of contact points of loose accumulation fragments is 3-10, most of the contact points of fragments are in the range of 5-7, and a small number of fragments have 10 contact points. The number of contact points of tight accumulation fragments is 4-11, most of the contact points of the fragments are in the range of 6-9, and a few of the contact points of the fragments reach 11. The number of contact points of the fragments of the tight accumulation body is more than that of the loose accumulation body.

[**Fig 7** is about here]

[**Fig 8** is about here]

The particle size of the fragments has a certain impact on the average number of contact points of the fragments. If the plane of the accumulation body is cut by another plane, then the shape of the fragments has nothing to do with the number of fragments per unit area n_s. Assuming that the average area of the outer surface of the k-th fragments is set as follows: under the condition that each pair of adjacent fragments has only one contact point, the average number of contact points of k-th fragments is as follows:

$$\overline{N}_{ck} = n_s \overline{S}_k \qquad (1)$$

In the formula, $\overline{S}_k = \pi d_{nk}^2$.

F_i represents the resultant force on the i-th fragment. It can be seen from Fig 9 that the force that F_i acts on the θ section is collectively referred to as the internal force of fragment. If the section θ cuts the fragments, the contact force P_{ij} acts on the part above the plane. At this time, the sum of the vectors of P_{ij} is the force F_i on each fragment, which makes the direction of the vector on each fragment and the magnitude of the vector all different.

[**Fig 9** is about here]

The effective stresses in the tangential and normal directions on the section θ can be expressed as:

$$\begin{cases} \tau_{zx} = \dfrac{1}{A_t}\sum_{i=1}^{m} F_{xi} \\ \tau_{zy} = \dfrac{1}{A_t}\sum_{i=1}^{m} F_{yi} \\ \tau_{z} = \dfrac{1}{A_t}\sum_{i=1}^{m} F_{zi} \end{cases} \qquad (2)$$

In the formula, m—represents the number of particles that may appear after cutting the accumulation body with this plane when the plane area is A_t.

As the direction and magnitude of the contact force change, the internal force component of the particle is:

$$\begin{cases} F_{xi} = \sum_{j=1}^{n_{ci}} P_{xij} \\ F_{yi} = \sum_{j=1}^{n_{ci}} P_{yij} \\ F_{zi} = \sum_{j=1}^{n_{ci}} P_{zij} \end{cases} \qquad (3)$$

Where n_{cj}—the number of contact points on the top of particle i;

P_{xij}, P_{yij}, P_{zij}—the components of the contact force P_{ij} on x, y, z.

2 Numerical Simulation of Excavation of Rescue Channel in Accumulation Body

2.1 Numerical Software and Modeling Principles

CDEM software is a new simulation software developed by using relevant knowledge of continuum mechanics and combining discrete element and finite element knowledge(Sun et al., 2015). The discrete element method is usually suitable for the study of the interaction force between the block particles in the collapsed accumulation body, and can better reflect the interaction between the block particles; the discrete element method can not only overcome the cumbersome problem of using the finite difference method, but also can improve the calculation accuracy.

This simulation was designed based on the following principles:

(1) Roadway collapse accidents after a coal mine disaster mainly occur in the mining roadway. The experiment mainly simulated the dynamic characteristics of the accumulation body and the mechanical mechanism between the accumulation body and the roadway under the condition that the accumulation body blocks the roadway after the mining roadway collapses. For the convenience of research, the numerical model only considered the stress factor, and appropriately simplified other factors.

(2) In order to meet the actual situation of the project to the greatest extent, in the excavation process of the simulated rescue channel, it is necessary to consider the mechanical effect of the collapsed accumulation body on the rescue channel support.

(3) The numerical model used the near sphericity and roundness of the accumulation to simplify the fragments into spherical particles of different sizes. Literature (Guo and Chen, 2016) and literature (Feng et al., 2012) jointly show that simplifying the particles accumulation body of accumulation body into spherical particles of different sizes, although there is a gap with the true shape of the accumulation body, it has little influence on the research conclusion.

2.2 Establishment of Numerical Model

Taking a coal mine of Hegang Branch of Longmei Mining Group in Heilongjiang Province as the engineering background, the roadway section was trapezoidal, and the height of the two sides: high side 3.4m, low side 1.8m, and lane width 2.5m. The roadway model was designed according to the scale of 1:40. The dimensions of the roadway model were: high side 8.5cm, low side 4.5cm, and lane width 6.25cm, ensuring that the model size is consistent with the actual size. The ratio of spherical particles was 1:100. The numerical model is shown in Fig 10.

[**Fig 10** is about here]

Generally, in order to reduce the amount of rescue channel excavation works, the rescue channel is excavated along the one side of roadway. According to the emergency rescue data, the section shape of the rescue channel should be rectangular, and the numerical model of the rescue channel should be 3.1cm high and 1.8cm wide. 8 monitoring points were set up at the intersection of the rescue channel and the supporting body. Among them, 4 monitoring points were evenly arranged on the top of the rescue channel, and 4 monitoring points were evenly arranged on the side of the rescue channel accumulation body. The rescue channel model and monitoring point settings are shown in Fig 11.

[**Fig 11** is about here]

In order to meet the actual situation as much as possible, referring to the geological data of the mine, the appropriate mechanical parameters of the spherical particles were selected, as shown in Tab 2.

[**Tab 2** is about here]

2.3 Numerical Simulation and Result Analysis

The excavation process of the rescue channel in accumulation body was simulated, and a picture was taken every 20,000 steps, as shown in Fig 12. Fig 12(a) shows the initial stage of the excavation of the rescue channel in the collapsed accumulation body. The original stable arch structure between the fragments and particles is destroyed; as the rescue channel is excavated to Fig 12(b), due to a large number of extremely unstable particles inside the accumulation body, these particles spontaneously move due to mutual compression and friction, and gradually reach a new equilibrium state; when the rescue channel is excavated from Fig 12(b) to Fig 12(c), the accumulation body, through continuous adjustment of itself, has formed a new arch structure and reached a new stable state. At this time, the friction and bite force between the particles of the accumulation body gradually increase, forming a temporary stable structure. The temporary stable structure exerts pressure on the support of the rescue channel through the transmission of the force between the particles. During the excavation of the rescue channel from Fig 12(c) to Fig 12(f), the temporary arch structure just formed collapsed due to the shear resistance generated after the particles contacted each other not enough to maintain the balance of the arch structure. The main reason is the phenomenon of “self-organization” of particles. Under the influence of “self-organization” movement, occlusion and friction occur between particles, causing the load to increase continuously, and the phenomenon of collapse occurs when the load limit is reached. The “self-organization” movement of the accumulation body is a process in which the original equilibrium state is broken and a new equilibrium state is formed. During this period, the displacement of the particles inside the accumulation body is constantly adjusted, and the adjustment of the particle displacement of the accumulation body is related to the formed arch structure. The bite force generated by the particles contacting each other is increasing, the displacement of the particles is very violent, and the arch structure formed by the particles has a violent settlement phenomenon. There are many random phenomena during the “self-organization” movement of accumulation body particles, such as the formation process of the arch structure and the collapse process of the arch structure. This kind of “self-organization” movement has a special dynamic phenomenon, that is, when the particle moves, there will be a force inside the particle to break away from the balanced structure, and this force is just expressed by the change of settlement. There is an arching effect in the process of particles forming an arch structure. Due to the arching effect, the direction of force action is changed, resulting in uneven force distribution. Due to the different sizes of particles in the accumulation body, the effects of the particles are also different. Large-diameter particles mainly play the role of a frame, and directly form an arch structure through occlusion and friction. Small-diameter particles mainly play a filling role and continuously fill a large number of pores. The accumulation body which has “self-organization” movement may also produce a random equilibrium state. After the original arch structure collapses, a new equilibrium state will be randomly formed. There is always a phenomenon of “self-organization” in the particles, and this phenomenon will disappear unless there are no gaps between the particles to pass through. The rescue channel advances from Fig 12(f) to Fig 12(h), the particle movement basically reaches a stable state, and the accumulation body terminates the “self-organization” movement.

[**Fig 12** is about here]

In order to study the mechanical mechanism between the internal arch structure of the accumulation body and the rescue channel during the excavation of the rescue channel, four sets of data of monitoring points 3, 5, 7 and 8 were selected, as shown in Fig 13.

It can be seen from Fig 13 that the peak stresses at the monitoring points are 164.06MPa, 169.25MPa, 152.19MPa, and 158.86MPa, respectively, and the peak stress is around 160MPa. The advancing time-steppings corresponding to the peak stress are 64330, 66740, 59199, and 60739, which are basically around 60000 time-stepping, which means that when advancing at 60000 time-stepping, a stable arch structure has been formed, and the arch structure acting on the support body of the rescue channel, the support body bears the greatest stress.

Before a stable arch structure is formed, the force at the monitoring point generally increases, but there is a sudden drop. This is because during the excavation of the rescue channel, in order to achieve a new balance, the accumulation body carries out “self-organization” movement. After the formation of a stable arch structure, with the excavation of the rescue channel, the arch structure is destroyed, and the accumulation body undergoes “self-organization” movement again, forming a new arch structure. From this point of view, the excavation process of the rescue channel is accompanied by much destruction and formation of arch structures.

At the initial stage of rescue channel excavation, the force that the support body bears mainly comes from its own gravity. At this time, the support situation is the most unstable, and a variety of support methods should be used to strengthen the support to prevent the occurrence of a second collapse accident from affecting the rescue work. After the stable arch structure is formed, the friction between the particles reaches the maximum value, the arch structure itself can bear part of the pressure, and the force acting on the support body is significantly reduced. During the entire excavation process of rescue channel, the force is initially small, then increases sharply, and finally tends to a stable equilibrium state.

[**Fig 13** is about here]

3 Discussion

During the numerical simulation of the excavation of rescue channel in the accumulation body, the movement trajectory of accumulation body particles is clearly visible; secondly, the movement of the fragments during the deformation process of the accumulation body in the roadway collapse is relatively clear. By observing and combining the above two aspects of fragment movement characteristics, it is not difficult to find that during the continuous "self-organization" movement of the accumulation particles, the accumulation particles appear horizontal, vertical, self-rotation, and multi-directional rotation. Therefore, there are four main types of adjustments in the process of "self-organization" of accumulation body fragments:

(1) Horizontal movement adjustment. As shown in Fig 14(a), block A is mainly subjected to horizontal force and starts to move horizontally under the action of the force until there is no room for movement. This situation mostly occurs in the early stage of the formation of the accumulation body, mainly at the bottom of the accumulation body, and the fragments are longitudinally restricted by the roadway floor.

(2) Vertical movement adjustment. As shown in Fig 14(b), block B is mainly subjected to pressure or impact from above, causing block B to continuously squeeze downwards, prompting adjacent blocks to move horizontally until block B is squeezed to a balanced state. In this process, block B has completed vertical movement adjustment, and adjacent blocks are adjusted for horizontal movement.

(3) Rotation movement adjustment. As shown in Fig 14(c), the initial state of the block C is an unstable state, and when it receives a force in a certain direction, it starts to rotate by itself until there is no more room for rotation.

(4) Multi-directional movement adjustment. As shown in Fig 14(d), the block D is subjected to multidirectional force, and the direction and magnitude of the force change with the self-organizing movement of the accumulation body, which promotes the multidirectional movement of the fragments of the accumulation body. Block D in the process of vertical movement adjustment also undergoes self-rotation adjustment. This method is the most important and common adjustment method for accumulation body blocks.

[**Fig 14** is about here]

Regarding the adjustment form in the process of "self-organization" of the accumulation body fragments, literature (Zhang et al., 2018) pointed out two adjustment forms of fragments: one is the adjustment of the lateral distance of the block; the other is the adjustment of the rotation of individual blocks. Among them, the adjustment of the lateral distance of the block corresponds to the adjustment of the horizontal movement of the block, as shown in Fig 14(a); the adjustment of individual block rotation corresponds to the adjustment of the rotation movement of the block, as shown in Fig 14(c). Through numerical simulation and field survey, it is found that the adjustment methods in Fig 14(b) and Fig 14(d) are also more common. The adjustment methods in Fig 14(b) mostly occur in the early stage of the "self-organization" movement of the accumulation body. The adjustment method in Fig 14(d) mostly occurs in the middle or late stage of the "self-organization" movement of the accumulation body.

4 Conclusion

(1) The morphological and structural characteristics, particle size distribution characteristics and contact characteristics of the collapsed deposits were studied. The formation of the accumulation body is a process of continuous "self-organization" adjustment of the rock fragments; along the direction of roadway axis, the accumulation body is divided into three areas: pre-sorting accumulation area, post-sorting accumulation area and non-sorting accumulation area; coal accumulation body is more broken and is prone to produce smaller fragments; the logarithm of the particle size-particle content distribution curve is a "bell-shaped" curve; the number of contact points of the fragments of the tightly accumulation body is more than that of the loose accumulation body. Before the excavation of the rescue channel, according to the geological characteristics of the fault fracture zone, the shape of the accumulation body can be estimated to provide support for rescue preparations.

(2) The CDEM software was used to simulate the excavation process of the rescue channel in the roadway collapsed accumulation body. The excavation process of the rescue channel is accompanied by the "self-organization" movement of the fragments; the macroscopic settlement deformation of the accumulation body is actually the process of the old arch structure continuously collapsing and the new arch structure continuously forming; During the excavation of the rescue channel, the force between the accumulation body and the rescue channel is initially small, then increases sharply, and finally tends to a stable equilibrium state.

(3) The self-organization adjustment method of the accumulation body was discussed and analyzed. The adjustment forms in the process of "self-organization" of the accumulated body fragments are mainly divided into: horizontal movement adjustment, vertical movement adjustment, rotation movement adjustment, and multi-directional movement adjustment. Among them, the multi-directional movement adjustment method of the block is the most common in the process of "self-organization" of the accumulation body, and it is also the most important adjustment method of the block.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (No. 51774122), the Natural Science Foundation of Inner Mongolia (No. 2020BS05007) and Inner Mongolia University of Science and Technology Innovation Fund (No. 2019QDL-B33).

Reference

Bai JW, Li SC, Liu RT et al (2015) Multi-field information monitoring and warning of delayed water bursting in deep rock fault. Chinese Journal of Rock Mechanics and Engineering 34: 2327-2335.

Chen GB, Qin ZC, Zhang GH et al (2020) Law of energy distribution before failure of a loaded coal-rock combined body. Rock and Soil Mechanics 41: 2021-2033.

Chen GB, Wang EY, Wang WC et al (2019) Experimental study on the influence of lithology and rock-coal height ratio on mechanical properties and impact effect of combined body. Energy Sources Part a-Recovery Utilization and Environmental Effects.

Cheng YH, Jiang FX, Hu XF et al (2016) "Prevention and control of coal burst on gob-side entry in deep coal seam with fully mechanized sublevel caving mining". Chinese journal of rock mechanics and engineering 35: 3000-3007.

Feng C, Li SH, Wang J (2012) Stability analysis method for bedding rock slopes under seismic load. Chinese Journal of Geotechnical Engineering 34: 717-724.

Gao MZ, Sheng W (2011) "Study on coal mine emergency refuge system construction in developed coal － producing countries". Journal of Anhui University of Science and Technology (Natural Science) 31: 13-16+67.

Guo HT, Chen GB (2016) "Research on numerical simulation of tunnel collapse deposit". Shanxi architecture 42: 54-55.

Hao CB, Zhang GH, Xiao FK et al (2013) "Study of collapse shape about mining gateway under condition of developed joints and fractures roof". Journal of Heilongjiang Institute of Science & Technology 23: 1-5.

Hao CB, Yu HJ, Zhang GH et al (2016) "Caving forms of roadway deposit underground geological fault fracture zone". Journal of Heilongjiang University of Science & Technology 26: 251-255+261.

He ZL, Liu W, He SM et al (2019) Shear dilatancy mechanism and process simulation of rapid sliding of saturated loose deposits. Rock and soil mechanics 40: 2389-2396.

Pu WL, Hao CB, Zhang GH (2017) "Study on mechanical properties of clogging deposit in mine flood changing slope point of roadway". Journal of Heilongjiang University of Science & Technology 27: 26-30.

Qin ZC, Chen GB, Zhang GH et al (2019) Tests on the dynamic failure rules of coal-rock composites. Acta Geodyn. Geomater 16: 39-54.

Qin ZC, Chen GB, Li T et al (2018) "Experimrntal study on determining 'key strata of energy' of rock burst". Journal of shandong university of science and technology (Natural Science) 37: 1-10.

Sun JP, Qian, XH (2017) "Emergency rescue technology and equipment of mine extraordinary accidents". Coal science and technology 45: 112-116+153.

Sun ZL, Kong Lw, Guo AG et al (2015) Surface deformations and failure mechanisms of deposit slope under seismic excitation. Rock and soil mechanics 36: 3465-3472,3481.

Wang K, Jiang SG, Wu ZY et al (2011) Research on the Shortest Path of Mine Emergency Rescue Based on Path Weight Adaptive Ant Colony Algorithm. Applied Mechanics and Materials 88-89: 302-306.

Wu Q, Xie KF, Chen ZY (2012) A catastrophe model on the evaluation and classification of mine disaster rescue measures. Systems Engineering Procedia 4:484-489.

Xia TQ, Zhou FB, Wang XX et al (2016) Controlling factors of symbiotic disaster between coal gas and spontaneous combustion in longwall mining gobs. Fuel 182: 886-896.

Yan WT, Dai HY, Chen JJ (2018) Surface crack and sand inrush disaster induced by high-strength mining: example from the Shendong coal field, China. Geosciences Journal 22: 347-357.

Zhang GH, Hao CB, Yu HJ et al (2014) "Analysis of collapse shape about mining gateway under condition of composite roof after disaster". Journal of Heilongjiang University of Science & Technology 24: 6-10+29.

Zhang GH, Li WC, Chen G et al (2017) "Simulation study on rescue channel position and section shape selection for accumulation body of collapse-caving". Journal of Heilongjiang University of Science & Technology 27: 1-7.

Zhang GH, Yu HJ, Hao CB et al (2018) Resistance force distribution law of collapse caving accumulation body's boundary in fault fracture zone. Journal of Mining and Safety Engineering 35: 532-537.

Zhang JB, Guo DY, Wang LB (2012) Study on mine emergency rescue organization structure model. Journal of china coal society 37: 664-668.

Figure lists

Table lists

Figures

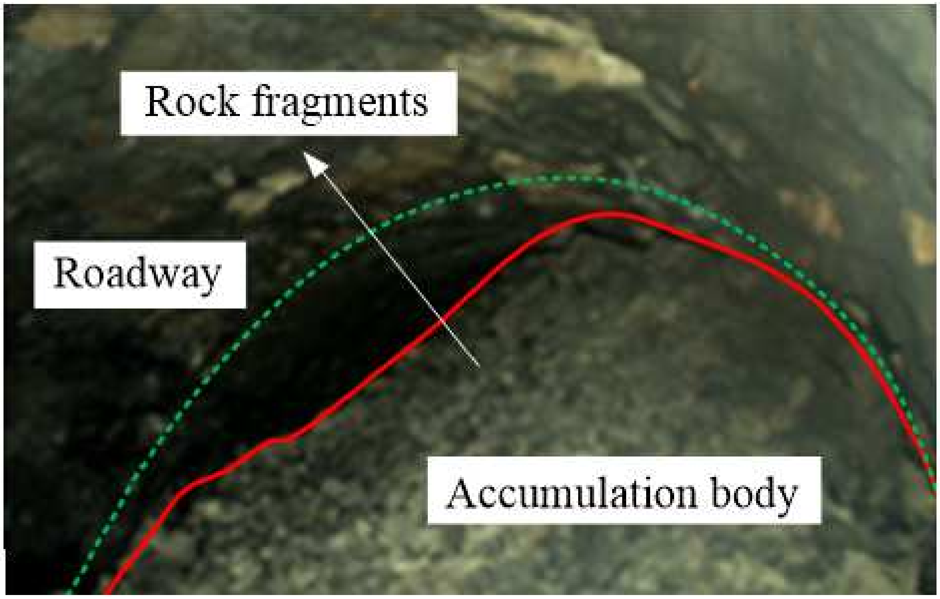


Figure 1

Collapsed accumulation body in fault fracture zone

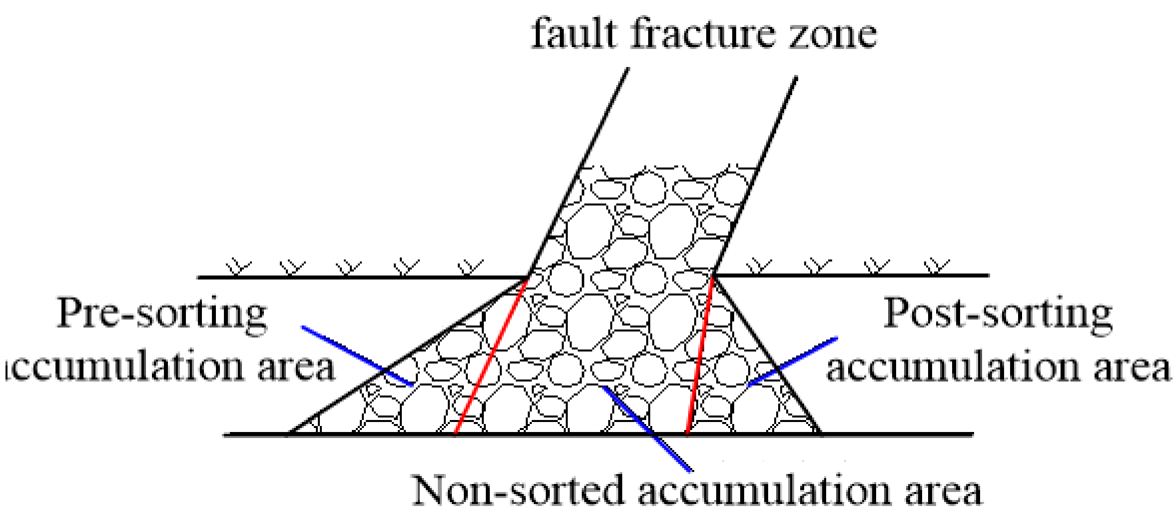


Figure 2

Zoning of collapsed accumulation body

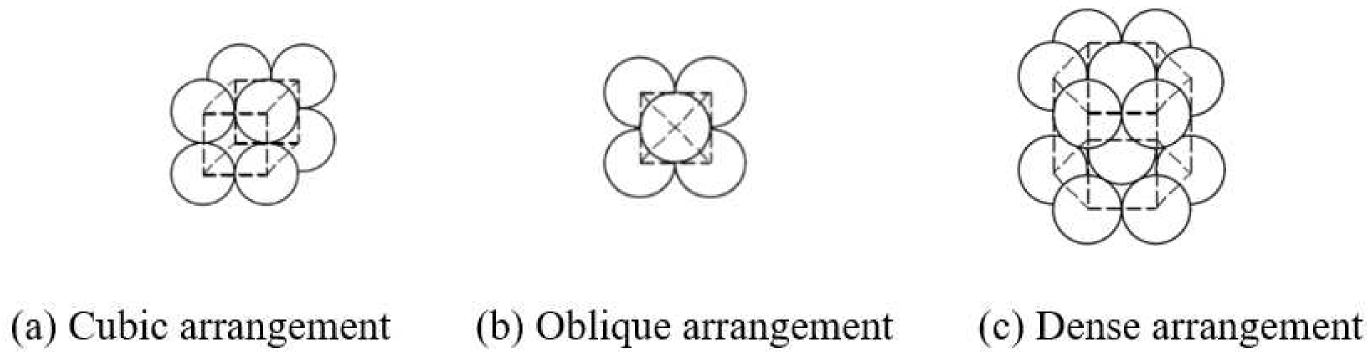


Figure 3

The accumulation method of accumulation body particles in an ideal state

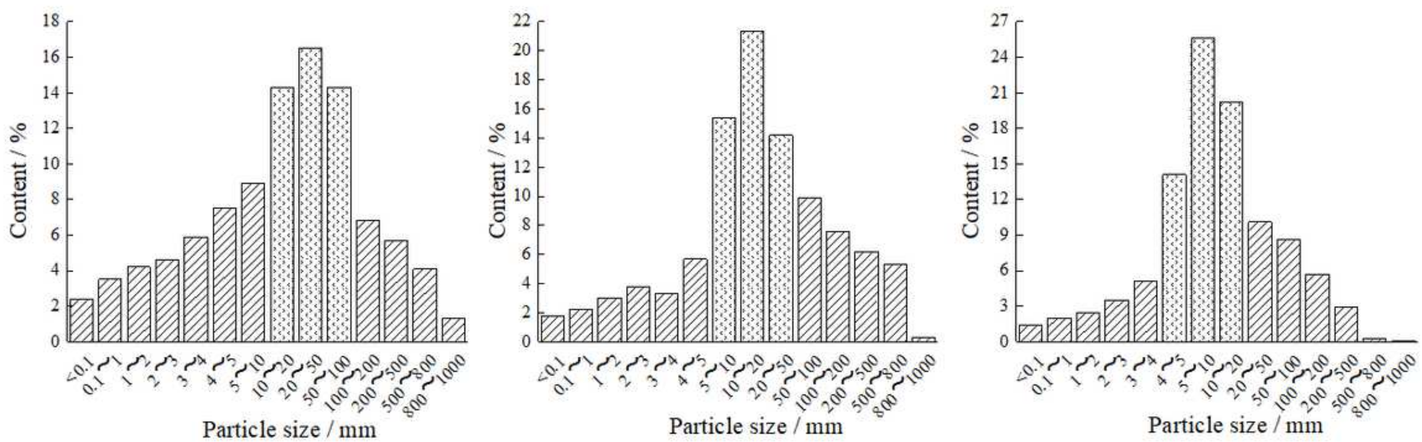


Figure 4

Histogram of particle size-content of three kinds of accumulation body

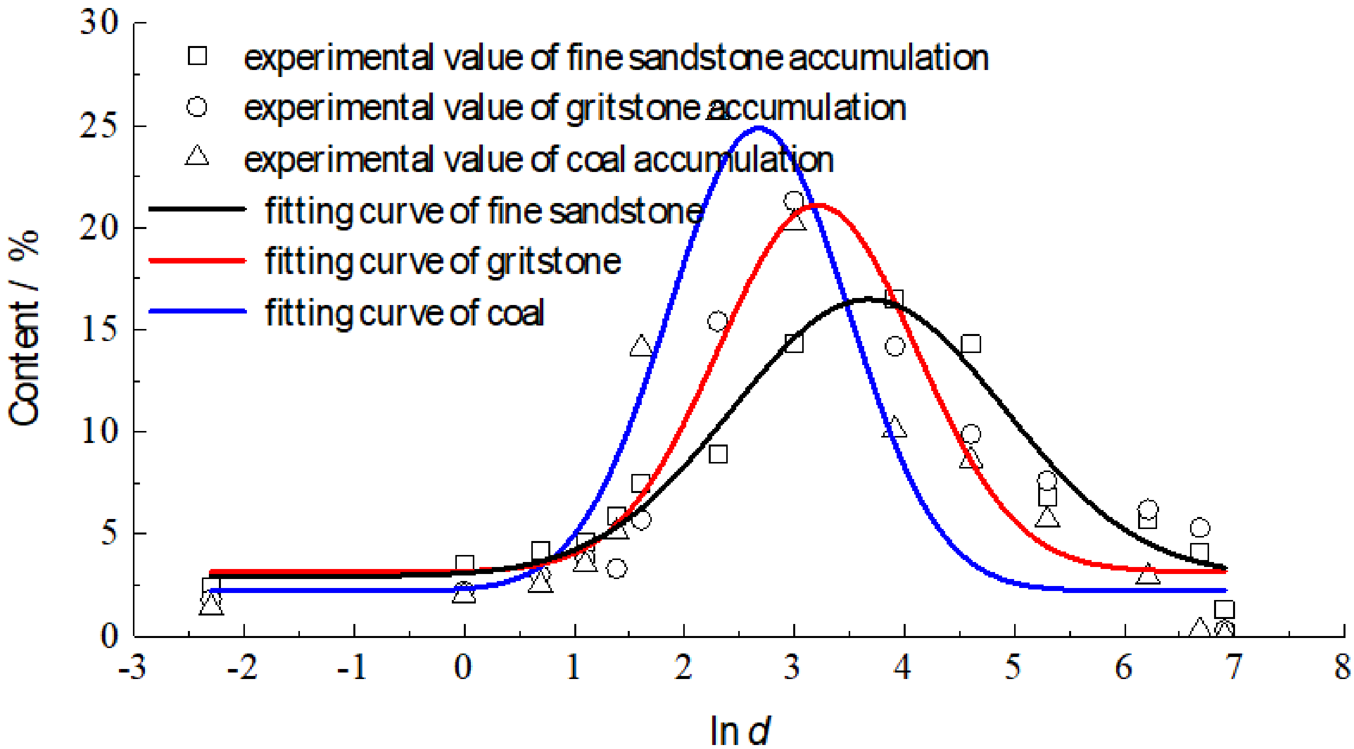


Figure 5

The logarithm-content curve of the particle size of the accumulation body

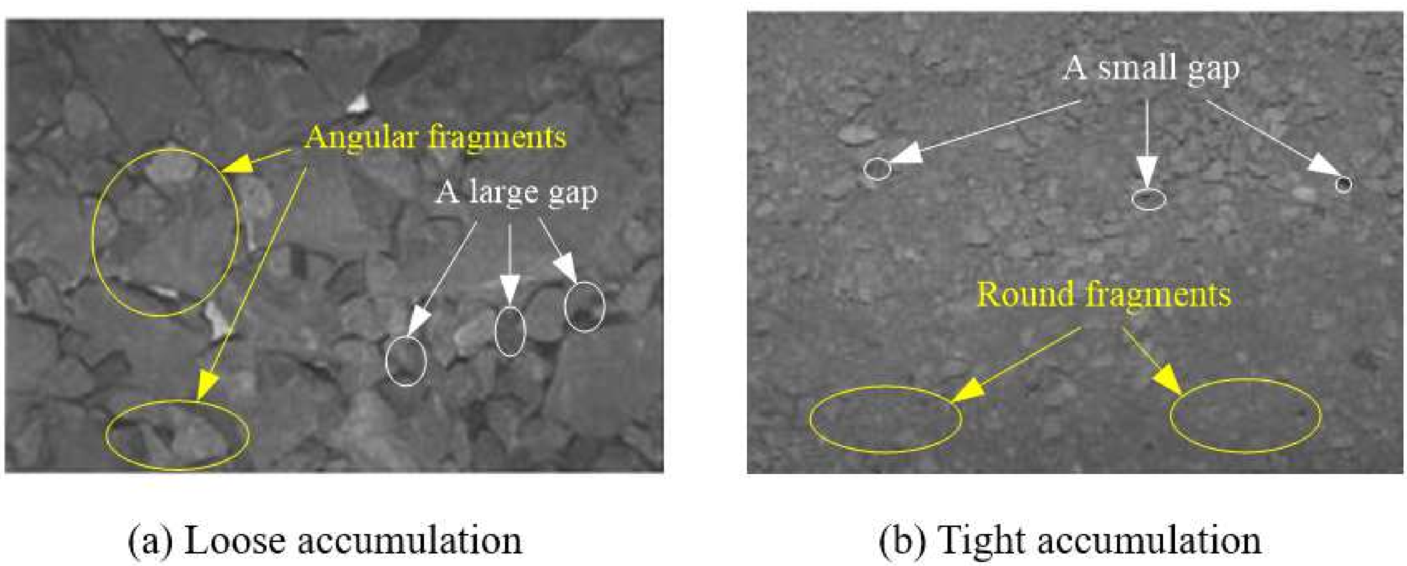


Figure 6

Contact situation of accumulation body particles

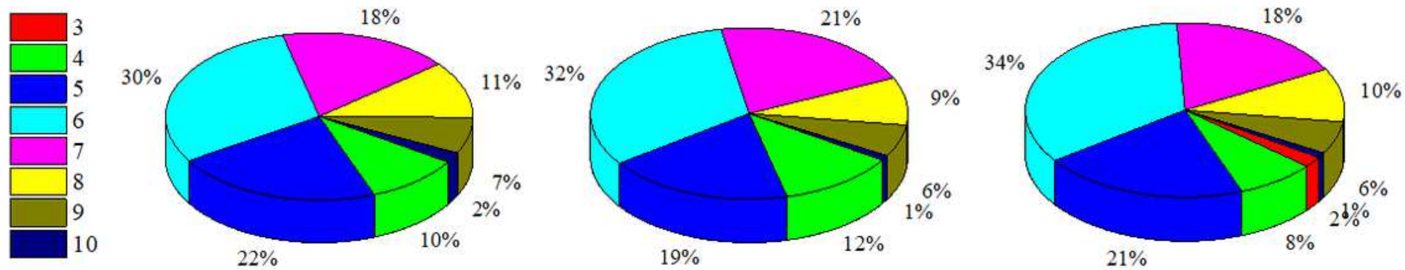


Figure 7

Number of contact points when loose accumulated

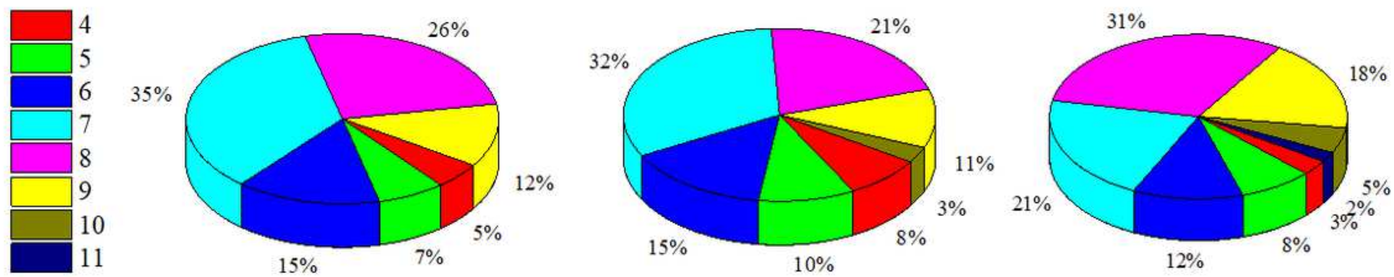


Figure 8

Number of contact points when tight accumulated

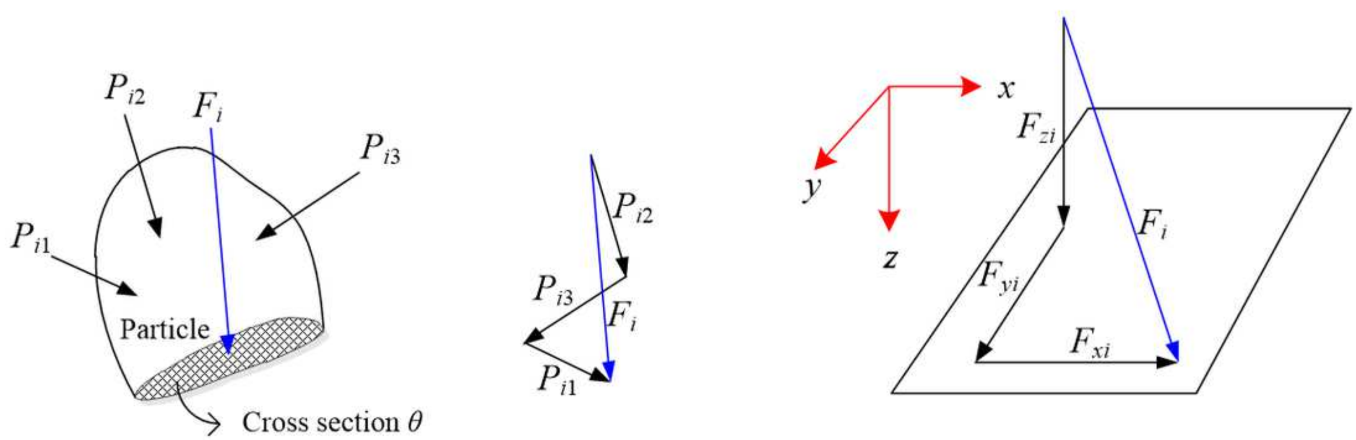


Figure 9

Particle internal force of accumulation body

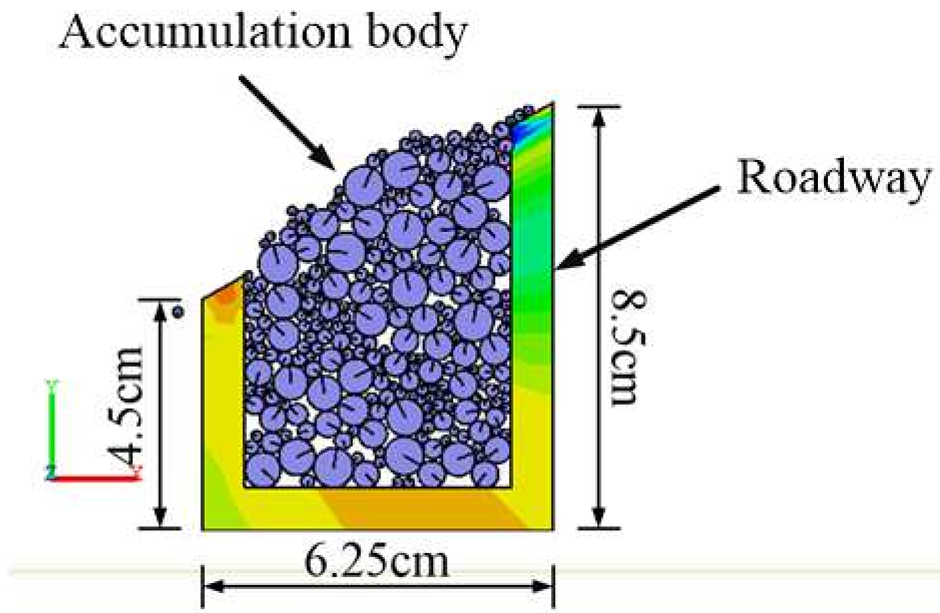


Figure 10

The simulation model of collapsed accumulation body in mining roadway

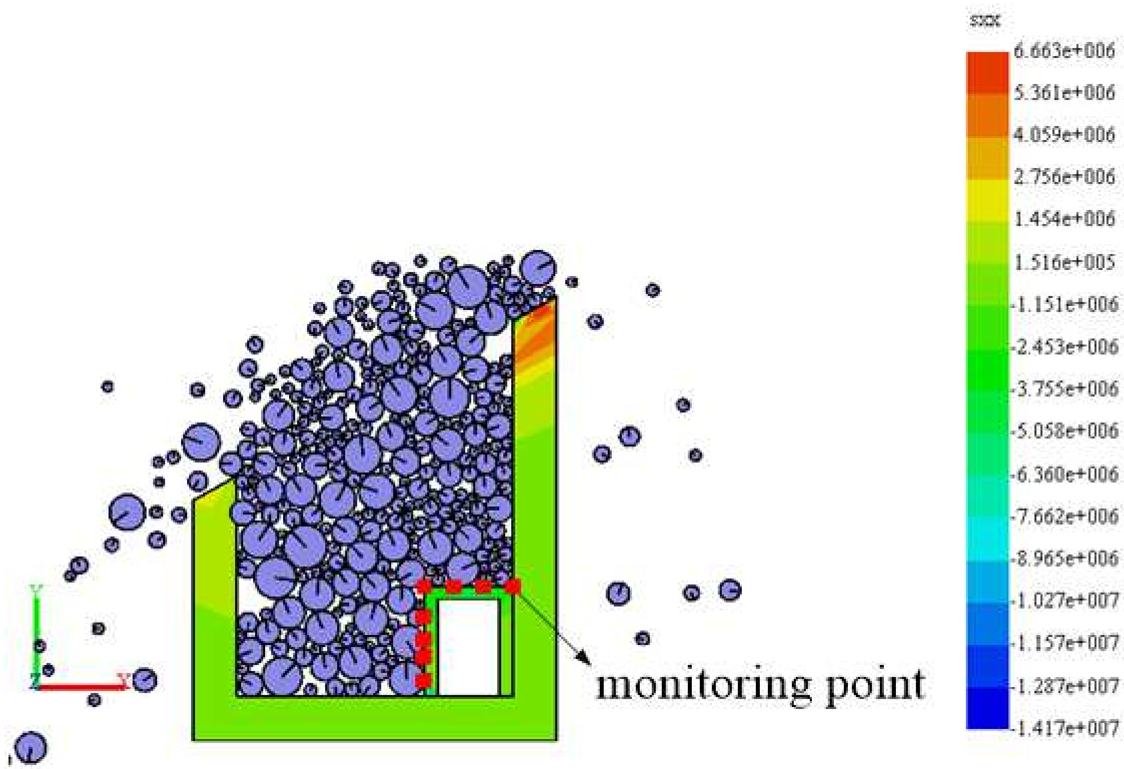


Figure 11

Excavation model of rescue channel in collapsed accumulation body

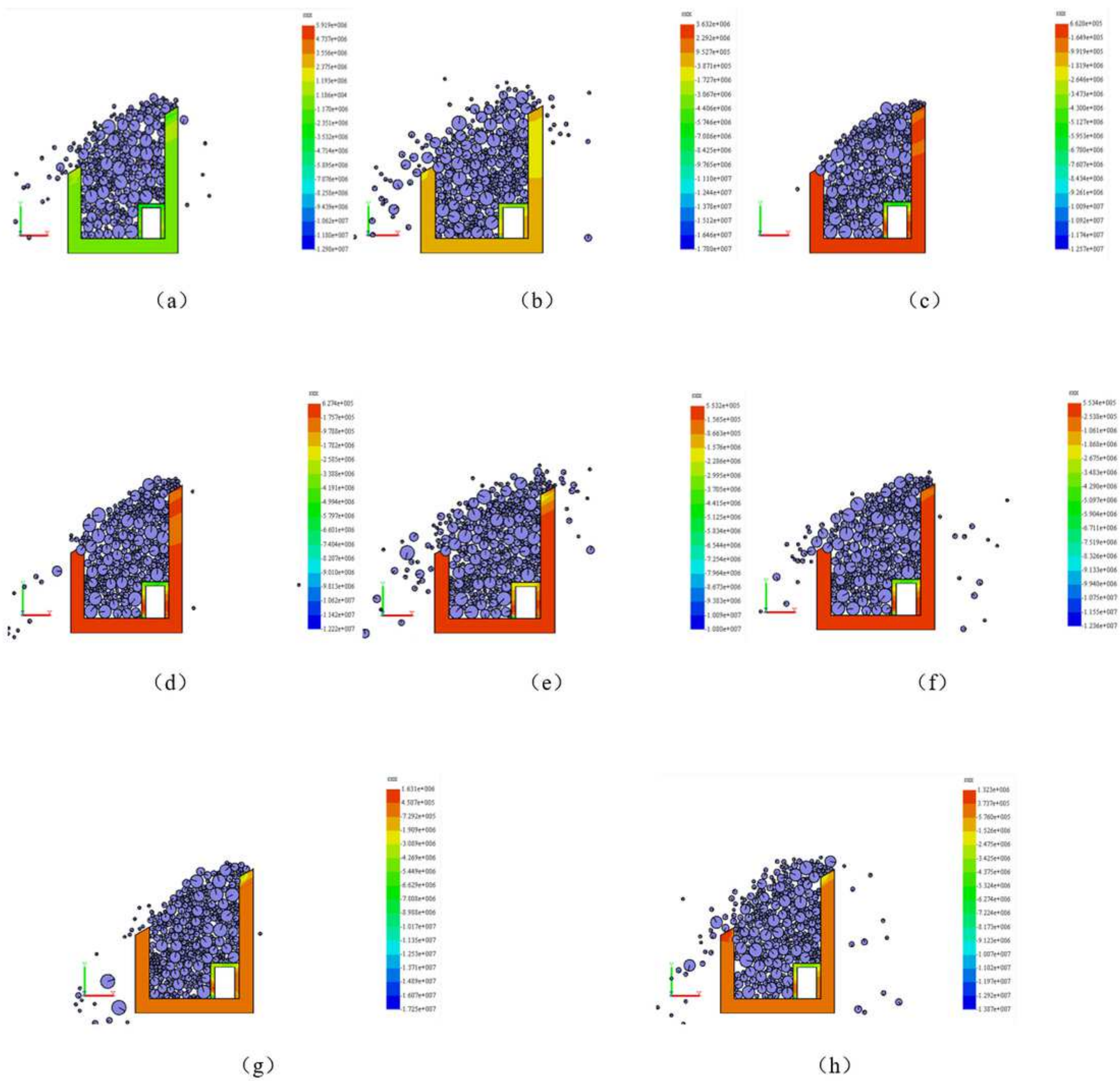


Figure 12

The excavation process of the rescue channel in the collapsed accumulation body

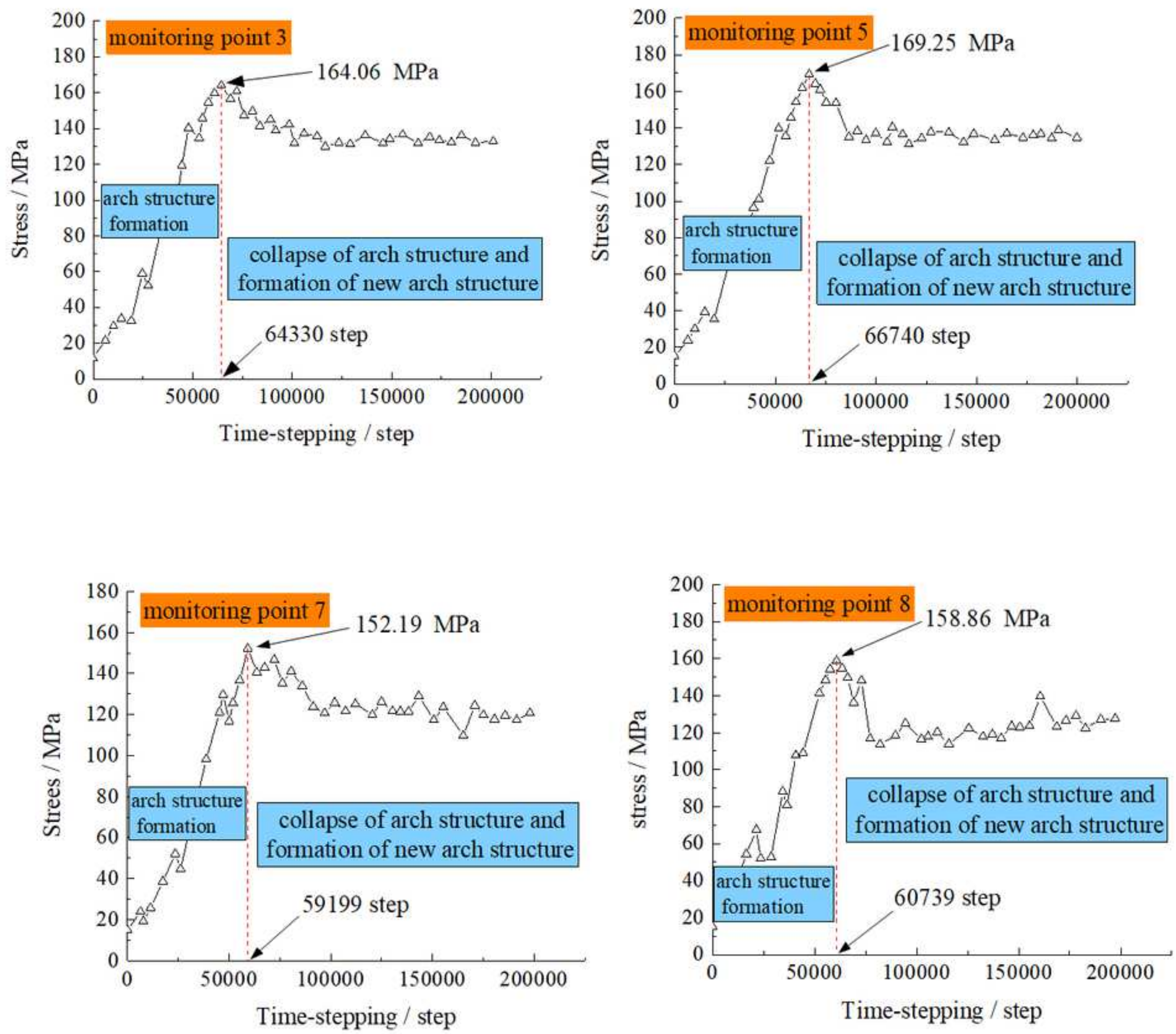
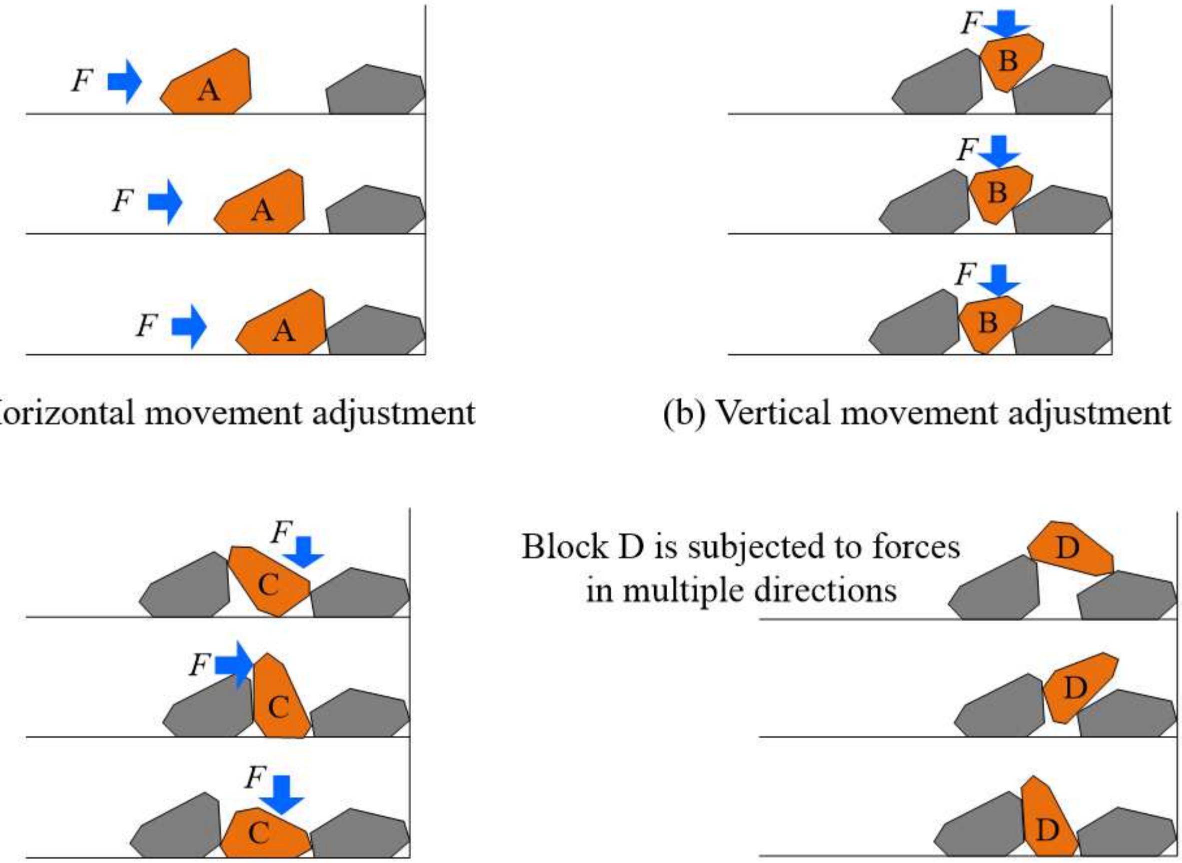


Figure 13

Forces at the monitoring points



(a) Horizontal movement adjustment (b) Vertical movement adjustment

(c) Rotation movement adjustment (d) Multi-directional movement adjustment

Figure 14

The adjustment form during the self-organization process of accumulation body fragments