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# Temporal and Spatial Evolution Law of Overlying Strata Collapse in Goaf

**Liu Mengke**

School of Safety Science and Engineering, Henan Polytechnic University, Jiaozuo 454000, China

**Abstract:** Goaf is a porous space formed by the dynamic collapse of coal seam roof after artificial excavation. Goaf is a serious disaster area affecting the safety of a basket. In order to explore the caving law of the overlying strata in the goaf with the increase of the advancing distance of the working face, the physical model of the goaf was built by using 3DEC numerical simulation software to simulate the caving of the overlying strata in the goaf. The results show that the subsidence of the overlying strata in the middle of the goaf is smaller than that of 500m, 700m and 900m when the working face advances 300m. With the increase of the advancing distance of the working face, the subsidence of the goaf increases or decreases, which indicates that the compaction degree of the central area of the goaf is higher, and the porosity of the central area is smaller, which has the environmental conditions of gas accumulation. In the process of change, the overburden caving in the goaf presents regularity. With the gradual advance of the working face, the rear roof of the goaf completely collapses, while the front roof gradually collapses with the advance distance until it completely collapses. In addition to cutting off the transmission of stress, the roof of the goaf at the roof cutting side makes the collapse more fully. The subsidence of the roof has no continuous change process and shows a jump decline. The vertical subsidence of the roof near the roadway area is close to the compaction area in the middle of the goaf.

**Keywords:** Numerical simulation; Goaf Collapse; Overlying strata

## 1. Introduction

China is a country rich in coal, short of gas and less oil. Coal is China's ballast1,2. Coal mine goaf has always been a serious disaster area with frequent accidents, and the safety management of goaf is an important factor affecting coal mine safety production3. Once the coal seam is mined, the overlying strata are prone to collapse to form a goaf. The goaf is a porous space formed by the dynamic collapse of the coal seam roof strata after artificial excavation activities, and its internal space is complex and difficult to enter artificially4–6. The treatment of collapsed goaf can effectively reduce the adverse effects of overlying strata collapse. Goaf is prone to spontaneous combustion of residual coal and gas overrun in working face. The caving mode of overlying rock in goaf affects the void ratio of goaf, thus affecting the air leakage in goaf, which is the prerequisite for the formation of spontaneous combustion of residual coal7–9.

Han et al used the finite element software MIDAS GTS NX to model and analyze the changes of slope stability coefficient under different excavation slope ratios in order to analyze the excavation stability and reasonable reinforcement measures of collapsed roadway and collapsed mining face slope in goaf10. Lu et al used the dome theory to study the progressive failure phenomenon of goaf under caving mining method. Based on the principle of moment balance, the prediction model of the section curve of the caving goaf is derived; In addition, the model is also used to estimate the stability of goaf and whether the height of collapsed rock is accurate. Then, the lateral pressure distribution of fractured rock with different particle size distribution under mining and overlying rock collapse is studied, and the effectiveness of the proposed prediction method is verified11. Ma et al found that under the influence of the space-time effect imposed by the slow creep of the column top system, it will collapse completely driven by the partial instability of the column top until the whole mine collapses, showing a domino effect. The dynamic process is ignored in the traditional mechanical stability analysis. Based on the analysis of the domino effect and disaster relief mechanism in the sheep in the mine, the dynamic analysis of the stability of the column top system was established by using the mechanical method and Voronoi diagram method. It seems to be more in line with the actual situation and can help to predict the time and place of the disaster more accurately12. Wu et al investigated the key role of goaf location in controlling deformation, failure mechanism and disaster evolution. Through field investigation and model generalization in Guizhou, three locations of goaf were studied by physical model test method: shoulder and foot of slope, under shoulder and inside slope. The research results emphasize that compared with the slope toe, the mutual position of goaf and slope shoulder has a greater impact on the deformation and failure of slope and overburden13. In order to solve the problem of uncertainty of overburden failure height and water loss in Daliuta coal mine, Shi et al used physical modeling, FLAC three-dimensional numerical simulation and field observation to study the overburden collapse characteristics and the development height of water flowing fracture zone, and verified each other 14. Wang et al used particle flow numerical simulation software PFC 3D to simulate the collapse of overlying strata. The quantitative porosity data of goaf was extracted and imported into fluent to simulate the air leakage flow field in goaf 15. Through physical model test, Wang et al studied the failure process and movement mechanism of overburden in steep slope multi seam stepped mining. The results show that in the initial stage, the main failure of the rock mass is the initial cutting and the small-scale collapse of the roof (the stability stage of the rock mass). After the roof is exposed for a certain distance, the rock mass in the downhill direction slides into the goaf and gradually destroys the interlayer in the goaf, which is similar to the displacement effect of dominoes (severe damage stage of rock mass) 16. Yu et al studied the collapse of the overlying coal pillar in the longwall working face, revealing the mechanism of coal pillar collapse and the disaster causing mechanism caused by strong earth pressure. The results show that the dynamic collapse process of coal pillar is relatively complex; First, the coal pillars on both sides of the goaf were damaged and unstable, followed by the adjacent coal pillars, which eventually led to large-scale collapse of the coal pillars17. Wang et al many voids are generated during the mining of ore bearing strata. In order to explore the development law of voids after mining coal bearing strata in goaf, a theoretical model was established, and the overall distribution and shape of voids in goaf were deduced. The above theory is verified by numerical calculation method, and the turning point of void change is found18. Luo et al used the deep hole caving method to gradually mine the gently inclined thick ore body in the tin mine test field under the complex filling body. The influence of complex backfill around stope on roof thickness, chamber and pillar stability in actual mining is studied; At the same time, the goaf formed in the mining process is so fragile that the surrounding rocks will collapse in advance. Based on this point, the roof thickness and span limit of goaf formed in mining are studied by using elasticity and limit span theory, and then a reasonable roof thickness of 8m and a goaf span of 14 m are proposed19. Zhang et al in this study, a comprehensive method including theoretical analysis and numerical modeling is proposed to study the failure characteristics of the overlying strata in shallow mining stopes20. Chen et al first conducted a physical model test to study the failure mode of the multi column roof support system. In the physical model test, it was observed that the design of the column was the same as the mechanical parameters in the model 1, and the roof above the slab column and barrier column cracked at the same time. When columns 2 to 5 lose their bearing capacity, the roof supported by these columns will collapse. The design of physical model is a relatively weak pillar among the six pillars21.

At present, the research on the complete spatio-temporal evolution law of Goaf Collapse is not clear. Based on this, taking Shancheng coal mine as the research background, the study on the collapse of the pumice layer in the goaf during the advancing process of the working face can provide some guidance and reference for the gas control and safety prevention in the goaf under similar conditions.

## 2. Principle of Overburden Caving in Goaf

The traditional caving method is mainly used to fill the mined-out area in most mines. This method has simple process and significant economic benefits and is often suitable for mines with direct roof prone to collapse. However, with the development of mining technology, this method gradually exposed obvious shortcomings, especially the severe disturbance to surrounding rock. For mines with long mining face and good roof, there are generally characteristics of long one-time caving period and large range, which are very easy to induce mine roof accidents, especially the overlying rock water flowing fracture zone formed by mining, which provides a channel for water and gas to flow into the mine, and has a direct impact on the safety production of the mine. Under the influence of geological conditions, mining technology, equipment level, working face layout and other factors, the stress of the roof rock under the coal pillar is much higher than that of the original rock, which brings huge potential safety hazards to the mining of the underlying working face. During the mining process of the underlying working face passing through the coal pillar area, strong ground pressure behaviors such as roof fall, slope deviation, water inrush and sand burst are easy to occur. What's more, dynamic ground pressure phenomena such as roof cutting and pressing frame, support column being crushed and column damage will occur, and it is often more dangerous when the working face pushes out of the coal pillar area.

In the process of longwall fully mechanized mining in large dip seam, there are many problems, such as the large number of people in the working face, the difficulty in controlling the surrounding rock and equipment, the low production and efficiency, and the frequent occurrence of flying gangue disasters. Especially in the mining of large dip and large mining height working face, due to the influence of gravity dip effect, there are significant differences in the stress state of overlying rock, the sliding filling characteristics of caving gangue, the three-dimensional fracture and migration law of overlying rock between the large-scale inclined stope and the stope of horizontal and gently inclined seam, which greatly affect the safe, stable and efficient control of the working face equipment and surrounding rock. It is urgent to carry out in-depth and systematic research in this area.

**Background**

Shancheng coal mine is located in the southern edge of Qinshui Basin on the west side of Taihang Mountains, which is a hilly area with low and medium mountains, developed valleys and ridges, and deep terrain cutting. The terrain in the mine field is high in the northeast and low in the southwest. The highest point of the terrain is located near Fanshan village in the north of the mine field, with an altitude of 1110.8m. The lowest point of the terrain is located near Daduan village in the southwest of the mine field, with an altitude of 647.6m. The maximum relative elevation difference of the terrain is 463.2m. The engineering background of this paper is 31001 mining face and goaf. Figure 1 shows the layout of 31001 mining face and goaf. The 31001 working face in Shancheng coal mine is the first working face in the 1 mining area of 3 × coal seam, with a strike length of 1060m and a dip length of 230m. The average coal thickness is 4.31M, and the average mining height of the working face is 4.5m. The working face adopts double roadway layout. The main mining seam of the working face is No. 12 coal seam, with an average distance of 47m from the overlying No. 2 × No. 2 coal seam. The roof of the 3# coal seam is sandy mudstone and fine-grained sandstone. The direct top is dark gray with thin layer of siltstone, and the sandy mudstone producing plant fossils, with a thickness of 2.89m; The main roof is fine-grained sandstone: gray, medium thick layered, mainly composed of quartz, containing star point muscovite. Argillaceous cementation, small cross bedding development, with fissures: Sandy mudstone: dark gray, dense, producing a small amount of plant fossils, with a thickness of 5.8m. The direct bottom is sandy mudstone or siltstone: gray, thin layer, containing star shaped muscovite, mixed with a large number of black argillaceous strips, showing gentle wavy bedding development, producing plant debris fossils.

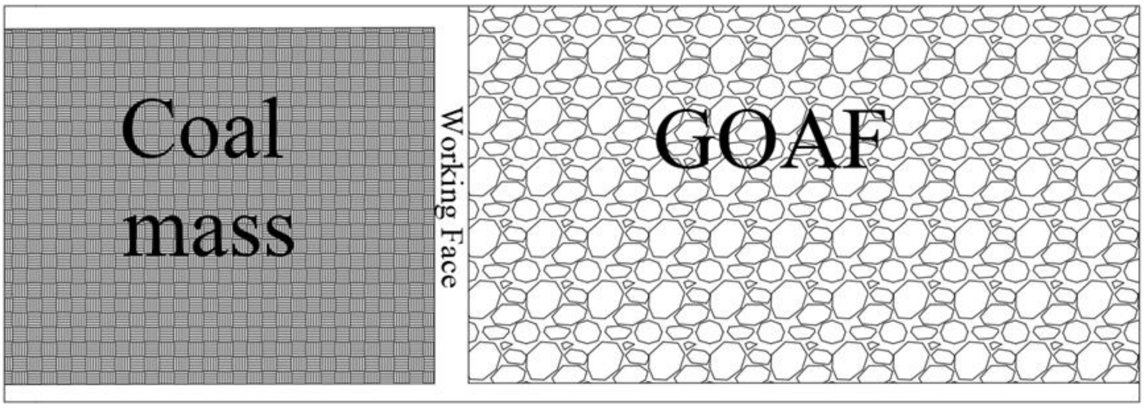


*Figure 1: layout of 31001 working face and goaf*

## 3. Numerical Simulation and Results of Overburden Caving in Goaf

### Introduction of numerical simulation software

3DEC characterizes the medium as a continuum of continuity and discontinuity features, uses convex polyhedron to represent the spatial features of continuous object elements in the medium, and uses surface (triangulation) to represent discontinuity features. The continuous characteristic object represented by convex polyhedron can implement the deformation and rigid deformation laws, and the fast Lagrange scheme is used to solve them. The numerical analysis method needs the help of computers. It belongs to a kind of simulation test, which imports the actual engineering situation into numerical analysis software, and simulates the actual situation in the computer software, which can combine theory and test at the same time and verify each other. The numerical analysis method is based on two basic modes, one is based on continuous medium, and the other is based on discontinuous medium. Continuous analysis methods such as finite element analysis, finite difference analysis, boundary element method and element free method. Discontinuous analysis methods include discrete element, particle element and manifold element.

The simulation process can be divided into building a physical model according to the simulated material, dividing the calculation area of the model, that is, dividing the grid elements, and then giving the material relationship and constitutive characteristics to the element grid and setting the boundary conditions, completing the above steps to obtain the physical model of the initial state, and finally carrying out the excavation calculation.

### Modeling

In this paper, 3DEC numerical simulation software is used to study the overburden caving characteristics of the goaf formed in the mining process of 31001 working face in Shancheng coal mine, and a three-dimensional numerical calculation model is established with the layout of 31001 working face and rock occurrence conditions in Shancheng coal mine as the simulation background, as shown in figure 2. The size of the physical model is 1100m (L) × 430m (W) × 80m (H). The working face of the test mine is 200m wide, the excavation along the strike direction is 1000m, the mining height is 4.5m, and the mining range is 250m × 300m × 5.15M. The dimensions of the auxiliary transport chute of the air inlet roadway, the rubber transport chute and the auxiliary transport chute of the air return roadway are 300m × 5.15M × 4m. In order to study the caving characteristics of overlying strata in goaf, 50m coal pillars are reserved at both ends of goaf strike and dip to eliminate the influence of boundary effect. The roof height is 62m, the coal seam floor is reserved for 14m, the roadway roof is obliquely cut, the cutting height is 9m, and the cutting angle is 10°.

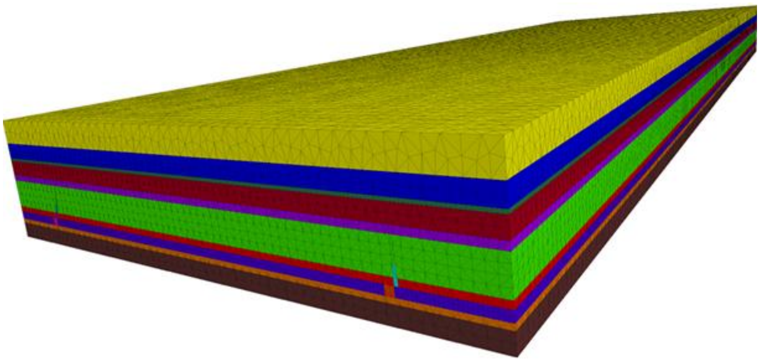

*Figure 2: three-dimensional numerical simulation model of overburden caving in Goaf*

### Spatio temporal evolution simulation of Goaf Collapse

The 31001 working face in Shancheng coal mine is the first working face in the first mining area of 3 × 3 coal seam. Two roadways are excavated first, and the return air roadway is pre cracked and roof cut, and the roadway on the other side naturally collapses. The goaf of 31001 working face is a one-sided roof cut goaf. Taking the layout of 31001 working face and the distribution of overburden rock in Shancheng coal mine as the background, 3DEC numerical simulation software was used to simulate the overburden rock collapse under the condition of unilateral roof cutting in this working face. The cloud chart of overburden rock subsidence of 900m in the numerical simulation excavation of 31001 working face in Shancheng coal mine is shown in Figure 3. In this study, 3DEC numerical simulation software was used to simulate the overburden caving law of the goaf during the excavation of 1000m in the goaf, and the working face advancing 300m.

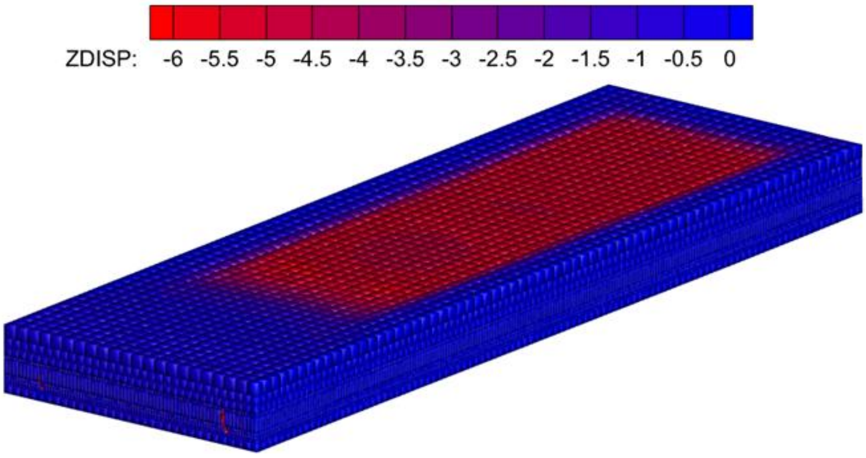


*Figure 3: Cloud chart of overburden subsidence after 900m excavation in Goaf*

Figure 4 shows the distribution diagram of vertical displacement in the inclined direction of the overlying strata in the goaf when the working face advances 300m-900m. It can be seen from the figure that when the working face advances 300m, the subsidence of the overlying strata in the middle of the goaf is smaller than that of 500m, 700m and 900m. With the increase of the working face advance distance, the subsidence of the goaf increases or decreases, which indicates that the compaction degree of the central area of the goaf is high, and the porosity of the central area is small, which has the environmental conditions of gas accumulation. In addition to cutting off the transmission of stress, the roof of the goaf at the roof cutting side makes the collapse more fully. The subsidence of the roof has no continuous change process and shows a jump decline. The vertical subsidence of the roof near the roadway area is close to the compaction area in the middle of the goaf. When the working face advances 300m, the dip direction of the goaf is 80m-115m, which is the variation area of the roof subsidence displacement of the goaf at the cutting side, and the subsidence displacement range is 0-3.75m. The roof of the goaf at the side without roof cutting collapsed less fully than that at the side without roof cutting. The subsidence displacement of the overlying strata decreased in a stepped manner. The closer the roof is to the roadway, the smaller the subsidence displacement is. The range of the dip direction of the goaf from 230m to 245m is the variation area of the subsidence displacement of the roof of the goaf at the side with roadway retaining. The subsidence displacement range is 0-3.5m, and the variation range is larger than that at the side with roof cutting. When the working face is advanced 500m, the dip direction of the goaf is 80m-115m, which is the variation area of the subsidence displacement of the roof of the goaf at the cutting side, and the subsidence displacement range is larger than that when the working face is advanced 300m. The roof of the goaf at the side without roof cutting collapsed less fully than that at the side without roof cutting. The subsidence displacement of the overlying strata decreased in a stepped manner. The closer the roof is to the roadway, the smaller the subsidence displacement is. The range of the dip direction of the goaf from 230m to 245m is the variation area of the subsidence displacement of the roof of the goaf at the side with roadway retaining. The subsidence displacement range is 0-3.9m, and the variation range is larger than that at the side with roof cutting. When the working face is advanced 700m, the range of the dip direction of the goaf 80m-120m is the variation area of the roof subsidence displacement of the goaf at the cutting side, and the subsidence displacement range is larger than that when the working face is advanced 500m. The roof of the goaf at the side without roof cutting collapsed less fully than that at the side without roof cutting. The subsidence displacement of the overlying strata decreased in a stepped manner. The closer the roof is to the roadway, the smaller the subsidence displacement. The dip direction of the goaf is 225m-255m, which is the variation area of the subsidence displacement of the roof of the goaf at the side with roadway retaining. The subsidence displacement range is 0-4.2m, and the variation range is larger than that at the side with roof cutting. When the working face is pushed 900m, the dip direction of the goaf is 80m-125m, which is the variation area of the subsidence displacement of the roof of the goaf at the cutting side. The subsidence displacement range is larger than that when the working face is pushed 700m. The roof of the goaf at the side without roof cutting collapsed less fully than that at the side without roof cutting. The subsidence displacement of the overlying strata decreased in a stepped manner. The closer the roof is to the roadway, the smaller the subsidence displacement. The dip direction of the goaf is 225m-255m, which is the variation area of the subsidence displacement of the roof of the goaf at the side with roadway retaining. The subsidence displacement range is 0-4.25m, and the variation range is larger than that at the side with roof cutting.

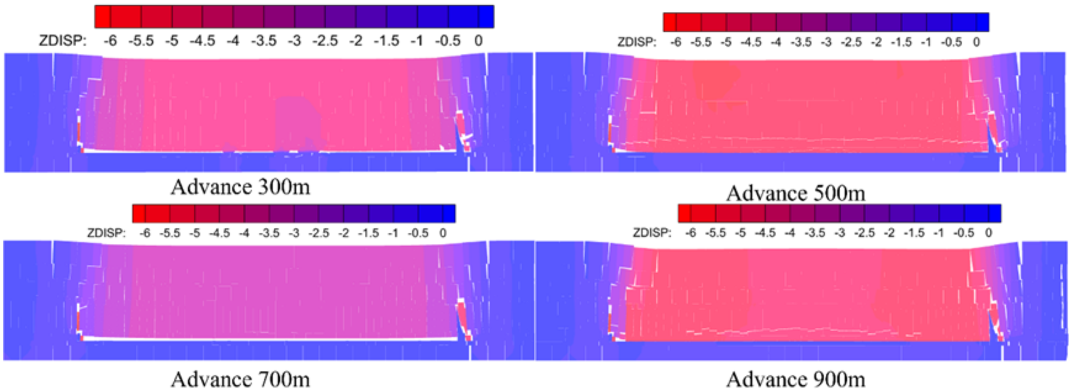


*Figure 4: distribution diagram of vertical displacement of overlying strata in dip direction in 300m-900m goaf pushed by working face*

Figure 5 shows the vertical displacement distribution diagram of the overlying strata in the top view direction of the goaf when the working face is pushed 300m-900m. It can be seen from the figure that when the working face is pushed 300m, the subsidence of the overlying strata in the middle of the goaf is smaller than that of 500m, 700M and 900m. With the increase of the working face pushing distance, the subsidence of the goaf increases, the compaction degree in the middle of the goaf increases, the subsidence of the overlying strata in the goaf near the working face is smaller, the overlying strata in the goaf near the working face are not fully collapsed, the compaction degree is low, and the porosity in this area is large, resulting in air leakage from the working face to the goaf. The central area of the goaf has a high degree of compaction, and the porosity of the central area is small, which has the environmental conditions of gas accumulation. When the working face is advanced by 300m, the length of the suspended roof is about 35m. With the increase of the advancing length of the working face, the length of the suspended roof has an increasing trend, the complete area behind the roof of the goaf continues to increase, and the proportion of the length of the suspended roof in the advancing distance of the working face becomes smaller. When the working face is advanced 500m, the length of the suspended roof is about 50m, which increases compared with the length of the suspended roof when the working face is advanced 300m. With the increase of the advancing length of the working face, the length of the suspended roof has an increasing trend, the complete area behind the roof of the goaf continues to increase, and the proportion of the length of the suspended roof in the advancing distance of the working face becomes smaller. When the working face is pushed 700m, the length of the suspended roof is about 60m, which increases compared with the length of the suspended roof when the working face is pushed 500m. With the increase of the advancing length of the working face, the length of the suspended roof has an increasing trend, the complete area behind the roof of the goaf continues to increase, and the proportion of the length of the suspended roof in the advancing distance of the working face becomes smaller. When the working face is pushed 900m, the length of the suspended roof is about 60m, which increases compared with the length of the suspended roof when the working face is pushed 700m. With the increase of the advancing length of the working face, the length of the suspended roof has an increasing trend, the complete area behind the roof of the goaf continues to increase, and the proportion of the length of the suspended roof in the advancing distance of the working face becomes smaller.

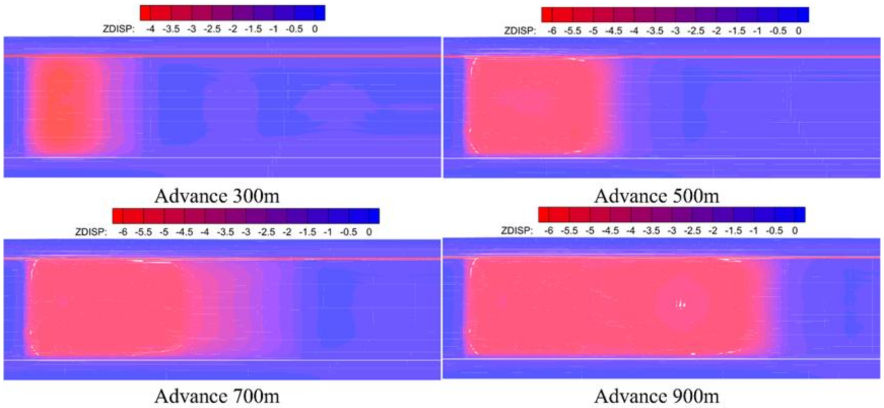


*Figure 5: vertical displacement distribution diagram of overlying strata in top view direction of 300m-900m goaf advanced by working face*

Figure 6 shows the distribution diagram of vertical displacement in the direction of strike of overlying strata in the goaf of 300m-900m advance of the working face. It can be seen from the figure that under the condition of roof cutting and pressure relief, when the working face is advanced to 300m, the roof of the goaf only has a small displacement, and the maximum displacement of the roof is 3.7m at x=155. There is a small deformation area in the area behind the roof of the goaf, and the average displacement of the deformation area is 2.37M, which is higher than other undeformed areas. It can be seen from the figure that under the condition of roof cutting and pressure relief, when the working face is advanced to 500m, the rear of the roof of the goaf presents a large displacement, while the front presents a small displacement. At this time, the maximum displacement of the roof is 4.53M at x=255. There is a large deformation area in the rear area of the roof of the goaf, and the average displacement of the deformation area is 4.34m, which is 2.23m higher than the average displacement of the deformation area in front of the roof. It can be seen from the figure that under the condition of roof cutting and pressure relief, when the working face is advanced to 700m, the roof in the back of the goaf collapses completely, and the collapse degree in the front increases continuously with the advance of the working face until it collapses completely. At this time, the maximum displacement of the roof is 4.59m at x=355. There is a large deformation zone in the area behind the roof of the goaf, and the average displacement of the deformation zone is 4.45m, which is 2.15m higher than the average displacement of the deformation zone in front of the roof. It can be seen from the figure that under the condition of roof cutting and pressure relief, when the working face advances to 900m, the complete caving area behind the roof of the goaf continues to increase, while the front of the roof continues to fully collapse with the advance of the working face, and a new caving area appears. At this time, the maximum displacement of the roof is 4.67M at x=455. There is a large deformation area in the rear of the roof of the goaf, and the average displacement of the deformation area is 4.55m, which is 2.47m higher than the average displacement of the deformation area in front of the roof.

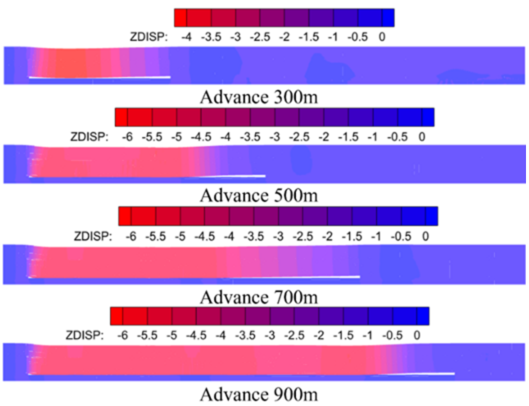


*Figure 6: distribution diagram of vertical displacement in the direction of strike of overlying strata in 300m-900m goaf pushed by working face*

Figure 7 shows the distribution data of the vertical displacement in the dip and strike directions of the overlying strata in the goaf 500m ahead of the working face, in which (a) represents the vertical displacement of the roof in the dip direction of the goaf, including the displacement changes of the roof at the cut side and the uncut side, and (b) represents the vertical displacement of the roof in the strike direction when the working face is 500m ahead. Taking the vertical displacement distribution data of the tendency and strike direction of the overlying strata in the goaf 500m ahead of the working face as an example. It can be seen from the figure that the vertical displacement of the overlying strata at the cutting top side decreases in a cliff like manner, while the vertical displacement of the overlying strata at the retaining roadway side is relatively continuous. From the vertical displacement of the roof in the strike direction, the vertical displacement of the goaf connecting to the working face is relatively continuous.

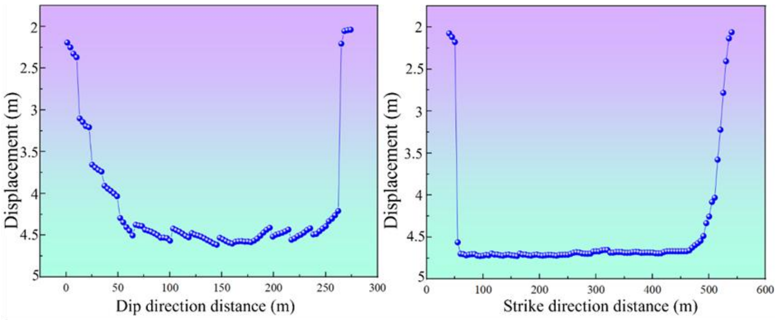


*Figure 7: distribution data of vertical displacement in the direction of dip and strike of overlying strata in the goaf 500m ahead of the working face*

## 4. Conclusion

1. Under the traditional mining mode, the goaf needs to be left with coal pillars to support the roof, which makes it difficult for the roof of the goaf in the area affected by coal pillars to collapse, resulting in the overlying strata of the goaf difficult to fully depressurize, while the roof of the goaf far away from the coal pillars is weakly affected by the coal pillars, and the roof can fully collapse after complete depressurization, resulting in large differences in the stress evolution and collapse characteristics of the overlying strata of the goaf inside and outside the area affected by coal pillars. The roof cutting and pressure relief mining mode makes the roof collapse directionally according to the height of the roof cutting by shaped charge blasting, and there is no need to leave coal pillar to support the roof, eliminating the coal pillar influence area, and the roof fully collapses, so that the overlying strata are completely relieved.
2. Compared with the traditional mining mode, the roof cutting pressure relief mining mode has more sufficient pressure relief, larger pressure relief range and global characteristics. In order to study and analyze the whole area pressure relief range of overburden rock in the goaf with roof cutting and pressure relief, the traditional mining mode and single side roof cutting and pressure relief mining mode were numerically simulated using the same lithology test, and the whole area pressure relief characteristics of the goaf with roof cutting and pressure relief were reflected through the comparison of different mining modes. In the process of advancing the working face, the overlying rock in the goaf has been in a dynamic state of "balance bending breaking collapse rebalance". In the process of change, the overburden caving in the goaf presents regularity. With the gradual advance of the working face, the rear roof of the goaf completely collapses, while the front roof gradually collapses with the advance distance until it completely collapses.

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