Study on the Carrying Capacity of Coal Goaf Based on Numerical Simulation

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Abstract. The stability of goaf surface is a key problem hindering the exploitation and utilization of goaf surface. By reproducing the process of goaf formation, the stability law of goaf is explored, and then the concept of load transfer depth is proposed [1], so as to obtain the method of calculating the surface carrying capacity of goaf, providing certain reference for the development and utilization of surface land resources in goaf in China.

1. Introduction

Our country’s coal resources have been exploited for many years, and a huge area of underground mined-out areas has been formed. With the development of urban construction, land resources have become increasingly tense. The land in coal mined-out areas has become an important resource for sustainable development. Contradictions are becoming increasingly acute.

In order to alleviate the contradiction between underground mined-out and above-ground construction, and realize better development and utilization of coal resources mined-out areas, this paper first establishes a three-dimensional simulation model for representative areas[2], simulates the excavation process, and completes the mined-out Study on the stability of the surface of the area, and then apply a load to the surface of the goaf to explore the carrying capacity of the goaf without measures [3], which can reflect the increased ground load of urban development and coal resource mining to a certain extent Interaction.

2. Study area

2.1. Study area location

This study analyzes the data of 23 mining areas in Jining that have been mined or are being mined, and select coal mines with complete geological data, borehole data, and stratum structure, obvious geological features, and strong representativeness as the study area. The coal mine in the study area is located in the northwest of Jining City. The center of the coal mine is 14km away from Jining City. The geographical coordinates are 116°28′30" ~ 116°32′30" east longitude, 35°29′30" ~ 35°32′30" north
latitude, north-south. The length is 4 ~ 4.5km, the width is 4 ~ 6km from east to west, the area is 20.8862km², and the elevation of the upper and lower limit of mining is -200 ~ -900m. The mine field is a plain landform. The terrain is slightly higher in the northeast and lower in the southwest. The ground elevation is 37.04 ~ 41.28m, the average elevation is 38.00m, and the terrain slope is 0.7‰.

2.2. Mining situation
The coal mines in the study area are mined at two levels: level one-386m and level two-500m. There are three mining areas at one level: 3 coal seams 130 mining area, 330 mining area and 16 coal seams 1160 mining area. There are four mining areas at the second level: 3 coal seam 230 mining area, 430 mining area, 530 mining area and 730 mining area. Among them, the coal seams in the 430 and 530 mining areas are seriously affected by magmatic erosion and have no recoverable reserves; the 730 mining area is due to ground mining is temporarily unavailable due to the compressed coal in villages and the thin bedrock under the loose aquifer of the Quaternary system. The mining sequence of the whole mine is the forward mining method, the mining method is the pseudo-inclined long wall receding coal mining method, and the roof management is the total caving method.

2.3. Rock Mechanics Experiment
In order to obtain accurate physical and mechanical analysis parameters, a total of 3 full-core drilling holes were arranged, and related parameter tests were carried out at the Experimental Center of Lunan Geological Engineering Survey Institute. The rock parameters are shown in Table 1 below.

| Table 1. Physical and mechanical parameters of each rock formation |
|---------------------------------------------------------------|
| **Type** | **Bulk modulus/GMPa** | **Shear modulus/GPa** | **Cohesion/MPa** | **Friction angle/°** | **Tensile strength/MPa** | **Density kg/m³** |
|-----------|------------------------|------------------------|-----------------|---------------------|-------------------------|------------------|
| Coal seam | 0.20 | 0.96 | 2 | 29 | 0.1 | 700 |
| The Quaternary Period | 2.80 | 1.07 | 3 | 30 | 1.01 | 1900 |
| Mudstone | 2.12 | 1.66 | 2.77 | 31.88 | 3 | 2510 |
| Sandstone with mudstone | 4.40 | 2.77 | 6.83 | 34.65 | 5 | 2320 |
| Fine sandstone | 2.76 | 2.11 | 6.5 | 41.21 | 6 | 2600 |
| Limestone | 2.84 | 2.05 | 3.92 | 35.08 | 6 | 2600 |

Note: The results are from the Experimental Test Center of Shandong Lunan Geological Engineering Survey Institute.

3. Establishment of numerical model

3.1. Constitutive model
In view of the geological situation of the study area, the Moore-Coulomb model constitutive model is used in the elastic-plastic simulation [4]. The Mohr-Coulomb strength criterion is a curve symmetrical to the σ axis in the τ-σ coordinate system. It can be obtained by experimental methods, namely by corresponding to various stress states (uniaxial tension, uniaxial compression and triaxial compression) Under the failure molar stress circle envelope[5], that is, the common tangent of each failure molar circle, called the molar strength envelope[6](Figure 1).
3.2. Model generalization

According to the general situation of the study area, the strata and coal seams are generalized. The overall model diagram is shown in Figure 2, and the model perspective is shown in Figure 3. The overall model of the coal mine in the study area has 1,728,385 nodes and 1,386,675 units.
For the impact of ground subsidence caused by excavation in the study area, the mining sequence is carried out in accordance with the time sequence of mining in each mining area [7]. The mining conditions are shown in Table 2. The model boundary uses displacement control conditions. The bottom of the model is three-way fixed constraint, the side of the model is horizontal and vertical constraints [8], and the top of the model is mainly affected by the stress of its own weight, which is a free boundary condition.

| Condition | 2001 | 2006 | 2010 | 2013 | 2018 |
|-----------|------|------|------|------|------|
| Condition-1 | 130 mining area completed | \ | \ | \ | \ |
| Condition-2 | 130 mining area after mining | 230 mining area completed | \ | \ | \ |
| Condition-3 | 130 mining area after mining | 230 mining area after mining | 1160 mining area completed | \ | \ |
| Condition-4 | 130 mining area after mining | 230 mining area after mining | 1160 mining area after mining | 330 mining area completed | \ |

4. Analysis of calculation results

4.1. Regional subsidence analysis
This time, only the results after mining of the coal seam of Working Condition 4 are analyzed. Working Condition 4 was completed in the 130, 230 and 1160 mining areas, but not on a completely stable basis. The mining area is 330. The mining area is then statically calculated, and the subsidence contour map is obtained as shown in Figure 4. There are few mined working faces in the 330 mining area. During coal mining, only 3301 working faces, 3302 working faces, 3305 working faces, and 3308 working faces are mined. There are only 4 mining working faces, but each mining face The coverage area is large, and each mining face has a large span. There is no coal pillar inside the mining face, which causes a large subsidence; the maximum subsidence is -4.31m.

After mining in the 330 mining area, the maximum subsidence directly above the 130 mining area stabilized at -5.69 meters, which was 0.7 meters more than the post-mining subsidence value of the 160 mining area -5.62 meters, accounting for 1.2% of the 130 mining area’s maximum subsidence. The subsidence in the 130 mining area is mainly affected by the mining of the 130 mining area, and the
mining correlation with the surrounding mining areas is weak, but compared to the 230 and 160 mining areas, the subsidence in the 130 mining area is most affected by the 330 mining area, reaching 1.3% of its own subsidence value. After mining in the 330 mining area, the subsidence of the 230 mining area stabilized at -5.26 meters, which was a change of 0.5m compared to the -5.21 meters before the 330 mining area was mined. During the 330 mining area, the 230 mining area subsidence center subsidence increased 0.5 meters, which shows that the subsidence of the 230 mining area is affected by the mining of the 330 mining area, but the impact is small, and the impact subsidence only accounts for 0.9% of the 230 mining area's own subsidence.

4.2. Subsidence analysis of the key section in the subsidence center of the mining area

(1) Subsidence analysis of 130 mining area

The surface subsidence curve of the I-I vertical section at the center of the subsidence funnel is shown in Fig. 5a, the II-II vertical section surface subsidence curve is shown in Fig. 5b, and the subsidence cloud diagram of the two key sections centered on the subsidence funnel center in the 130 mining area is shown in Fig. 6a.

There are two subsidence funnels in the subsidence curve of section II. The mined area of this line has 130 mining area and 230 mining area. There is the maximum subsidence value of this section at the 130 mining area, and the subsidence at the boundary of the study area is small, which shows that the study Mining of coal seams in the district has less impact on the periphery of the goaf.

The II-II section subsidence curve has two subsidence funnels. The goaf that the line passes through is only 130 mining area, but there are four large mining face groups in the 130 mining area. The II-II section subsidence curve passes through 1305/1307 working face group and 1306/1308 working face group. So there are two sedimentation funnels.

(2) Subsidence analysis of 230 mining area

The surface subsidence curve of the vertical section III-III at the center of the subsidence funnel is shown in Fig. 5c, and the surface subsidence curve of the vertical section IV-IV is shown in Fig. 5d. The
The subsidence curve of section III-III has two subsidence funnels. The goaf of this line has 130 mining area and 230 mining area, and the maximum subsidence value is at 230 mining area.

The IV-IV section subsidence curve has only one subsidence funnel, and only 230 mining areas pass through the goaf. The maximum subsidence of this section is in the 230 mining area.

(3) Subsidence analysis of 230 mining area

The surface subsidence curve of the V-V vertical section at the center of the subsidence funnel is shown in Fig. 5e, and the surface subsidence curve of the VI-VI vertical section is shown in Fig. 5f. The subsidence cloud diagram of the two key sections centered on the subsidence funnel center of the 130 mining area is shown in Fig. 6c.

The V-V section subsidence curve has two subsidence funnels. The mined-out area of the line has 330 mining area and 230 mining area, and the maximum subsidence value is at the 330 mining area. The subsidence curve of the VI-VI section has only one subsidence funnel, and the goaf of the line has 330 mining areas and 130 mining areas. The maximum subsidence of this section is in the 330 mining area.

Figure 5. Surface subsidence curve of section
Figure 6. Surface subsidence cloud diagram of section (a: Surface subsidence cloud diagram of section I-I and II-II b: Surface subsidence cloud diagram of section III-III and IV-IV c: Surface subsidence cloud diagram of V-V section and VI-VI section) Unit:m

5. Analysis of surface bearing capacity of mined-out area

5.1. Overview of building load influence depth
The study of surface city construction in coal resources mined-out areas is different from mining subsidence studies. Its essence is to study the establishment of large-scale urban structures on the surface of a stable empty area [9]. Due to the loads and disturbances caused by urban structures and human activities, a disturbance area with redistribution of stress and strain is formed in a certain range below the ground surface [10]. When this disturbance zone overlaps with one or more of the bending zone, fault zone, and collapse zone caused by the underground goaf, it will destroy the original equilibrium state of the collapse zone and make the rock The inside of the body moves again, and this movement will spread to the surface [11-12]. The mined-out area is reactivated, the stable ground surface moves again, and it reacts to the newly-built urban structures, causing uneven subsidence of the foundation [13], leading to the destruction of the building.

Domestic scholars have proposed to use whether the depth of the collapsed fault zone in the goaf and the depth of the additional stress of the building load overlap to determine the stability of the foundation in the goaf[14]. The relationship between the depth of the collapsed fracture zone and the depth of the additional stress of the building load [15], when there is a certain distance between the depth of the additional stress of the building and the depth of the collapsed fracture zone, the building load above the goaf will not affect The stability of the collapsed fault zone, when the foundation of the building is in a stable state. When the depth of the additional stress of the building coincides with the depth of the collapsed fracture zone, the foundation of the building is in a critical state. When the depth of the additional stress of the building and the depth of the collapsed fracture zone overlap each other, the building load above the goaf will affect the stability of the collapsed fracture zone, and the building site is in an unstable state at this time.
5.2. Depth study of building impact

Surface buildings in the mined-out area have the greatest pressure on the surface, which is the weight of the building itself. As the depth increases, the self-weight stress of the foundation soil gradually increases, while the additional stress generated by the newly built building gradually decreases. It is generally believed that when the additional stress generated by a new building is equal to 10% of the self-weight stress of the foundation at the corresponding position [15], it can be considered that the additional stress generated by the building has no effect on the foundation at this depth. At the extreme value of the depth of influence of the building load, the vertical displacement generated under the action of the building load is small, and the influence on the stability of the goaf is negligible.

On the basis of the completion of coal mining in the study area, the stress and displacement fields after mining in the study area have been obtained. By clearing the post-mining displacement field, and then applying building loads on the surface, the mining can be adjusted according to the depth of the additional stress. The suitability of urban construction in the empty area is evaluated.

However, considering the large area of urban planning, there are many uncertain factors. According to the simulation analysis of the impact of construction load on the stability of the goaf, ordinary multi-storey buildings are selected for evaluation. Assuming that on the surface of the mined-out area with the smallest mining depth (280 meters), the highest number of floors in the urban planning area is seven-storey residential buildings. The new strip-shaped residential building is calculated as an example with a length of 60m and a width of 10m. The buried depth of the base is 3.0m, the load of the building is 18kN/m² (the size of the single-story building area load), the number of floors to be built is considered 4, 5, 6, and 7 stories, and the building load imposed on the surface is 72kN respectively /m², 90kN/m², 108kN/m², and then perform static calculations, use FLAC3Dfish language to extract the formation deformation value, obtain the depth of the additional stress, and refer to the critical depth of the load to quantitatively evaluate the stability of the goaf by engineering construction. The evaluation criteria of the degree of sexual impact are shown in Table 3 to evaluate the suitability of urban construction in the goaf area.

Table 3. Quantitative Evaluation of Critical Influence Depth of Load Evaluation Standards for the Influence of Engineering Construction on the Stability of Goaf

| Evaluation factor | Influence degree | 4 | 5 | 6 | 7 |
|-------------------|------------------|---|---|---|---|
| Additional stress influence depth \( H_a \) and collapsed fault zone depth \( H_{if} \) | \( H_y < H_a \) | \( H_a \leq H_{if} < 2.0H_a \) | \( H_{if} \geq 2.0H_a \) |

Gradient building loads are applied to the surface, and after static calculations, a cross-sectional strain map of the mined-out area is obtained (Figure 6). Using the FLAC3Dfish language, the stratum displacement and stress can be extracted, and the depth of influence of the additional stress of the building load can be obtained, and the fracture can be calculated according to the formula method. The height of the collapse zone is the depth of the collapse fracture zone. The calculation results are shown in Table 4.

Table 4. Depth result table of building load influence

| Building floor number | Building load (kN/m²) | Influence depth of additional stress of building load (m) | Depth of failure zone (m) | Minimum mined-out area depth (m) |
|-----------------------|-----------------------|----------------------------------------------------------|---------------------------|---------------------------------|
| 4                     | 72                    | 8                                                        | 203.76                    | 280                             |
| 5                     | 90                    | 18                                                       | 203.76                    | 280                             |
| 6                     | 108                   | 23                                                       | 203.76                    | 280                             |
| 7                     | 126                   | 30                                                       | 203.76                    | 280                             |
Figure 7. Sectional strain slice diagram of goaf

Figure 7 shows the strain of various layers above the goaf under the building load. It is found that the maximum strain at the collapsed fault zone is only 1.5 mm, and the maximum strain on the ground is 0.08 m, which is only 1% of the ground surface, which can be ignored. The strain value at the falling fault zone is very small, so the building load has little effect on the stability of the goaf in the study area.

With reference to the evaluation criteria for the quantitative evaluation of the impact of engineering construction on the stability of the goaf with reference to the critical impact depth of the load, it can be seen that under the four building loads, the depth of the collapsed fracture zone is 203.76 meters, and the maximum impact depth of the additional stress of the building load is 30 meters. When $H_d \geq 2.0H_{cr}$, the surface of the coal mine goaf in the study area, and the additional stress of building load has little effect on the goaf. The coal resources goaf in the study area may cause sudden instability of the goaf under the action of construction load. Less sexual

6. Conclusion

This paper uses numerical simulation to study the response law of the whole process of coal mining in the study area, and then applies gradient loads on the surface of the goaf. By studying the load transfer depth, the surface bearing capacity of the goaf is explored, which is the development of the surface land resources of the goaf in my country. Utilization provides a certain reference and obtains some meaningful conclusions for the development and utilization of mined-out areas:

1) In the study of the stability of the goaf in a large area, numerical simulation can be carried out by grasping the main limiting factors to simulate the whole process of goaf mining to explore the stability of the goaf. In the example of this paper, multiple subsidence funnels are formed on the surface of the goaf. The maximum subsidence is at the center of the funnel. The farther away from the subsidence center in the same direction, the smaller the subsidence. The most subsidence of the surface occurs in the 130 mining area, and the maximum subsidence displacement is -5.69m, the displacement shows a decreasing trend from the middle to the surroundings, and the displacement decreases to 0m at the boundary of the basin; in the vertical section, the displacement of the coal roof in the goaf is the largest, and the displacement shows a decreasing trend from the roof to the surface. An upward bulge appears on the floor of the goaf, and the bulge displacement is 0.27m, which appears on the coal seam floor of the 1301 working face.
(2) Numerical simulation methods can be used to study the bearing capacity of the mined-out area to study the relationship between the depth of the additional stress of the building load and the depth of the collapsed fault zone and the minimum mined-out zone depth, and to quantitatively evaluate the impact of the engineering construction on the mined-out area with reference to the critical depth of the load. The evaluation standard of the influence degree of the stability of the area is determined. The minimum mining depth of the study area is under the load of a 7-story building, and the additional stress has a small influence on the goaf, and the possibility of activation instability of the goaf is small, but Under the long-term action of natural stress, the goaf may creep slowly.

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