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Prediction of surface subsidence in Gequan coal mine based on probability integral and numerical simulation

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Abstract: *The goaf produced by underground mining will produce subsidence on the surface, which will threat to the overlying buildings. In order to study surface subsidence, probability integral method and FLAC3D numerical simulation method were adopted to simulate and predict the coal seam mining in Gequan Mine. The results showed that the subsidence decreased gradually from the center of the goaf to both ends, from the underlying strata to the surface, and the result of probability integral calculation was slightly larger than that of numerical simulation. However, in the case of fully considering complex strata and insufficient mining, numerical simulation can better reflect the real situation in the mining surface subsidence of Gequan Mine, which has good reference significance.*

Keywords: *Goaf, Probability integral method, Numerical simulation method, Surface subsidence*

1. Introduction

The rapid development of the Chinese economy has led to continuously increasing energy consumption and demand. Despite China actively promoting the development of renewable energy [1], and gradually introducing some new energy sources, coal still holds a significant proportion in China's energy structure, accounting for 56.80% of the nation's total energy consumption [2]. In order to adapt to this situation, the mining engineering industry is also developing rapidly, continuously engaging in large scale coal resource exploitation. By the end of 2021, the national raw coal production in China had reached 4.07 billion tons, accounting for 51.60% of the global total output, of which 85% came from underground mining [3]. Consequently, China is now the country with the highest coal production and the largest proportion of underground mining in the world. The exploitation of coal resources holds crucial strategic significance for the long-term development of China. However, simultaneously, the excessive exploitation of underground coal resources has resulted in severe secondary disasters, which have had caused significant impacts on the ecological environment [4].

When mining underground seams, the stress balance of surrounding strata will be disrupted, resulting in the formation of goaf. During this process, the strata and surface will experience continuous movement, deformation, and discontinuous failure (such as cracking, caving, etc.), which is called "mining subsidence" [5]. If the range of underground mining is small and the buried depth of mined minerals is large, the affected range of mining subsidence is usually limited to the rock mass around the mining area. If the mining range is large and the mining depth of minerals is small, the affected range of mining subsidence will develop from rock mass to the surface, causing surface movement [6]. Many practices proved that the range of overlying strata and ground surface movements (subsidence and deformation) have the creep property, which is the main factor of dynamic ground subsidence [7, 8]. The subsidence resulting from mining activities has altered the initial topography and geological formation of the goaf, disrupting the ecological balance within the mining area. It has impacted the stability of structures, including roads, bridges and buildings, consequently hampering the sustainable progress of the mining area. The research and treatment of land subsidence has been a global problem, prompting numerous scholars to conduct extensive research on mining subsidence and its associated issues [9, 10].

At present, experts from home and abroad have put forward a variety of schemes for theoretical prediction of mining subsidence. As early as 1953, Knothe introduced the Knothe function to predict dynamic surface subsidence [11]. Zhang et al. established an improved Knothe time function model, which accurately predicted surface subsidence caused by underground mining [12]. Wang et al. identified the defects in the improved Knothe time function and provided a more accurate dynamic prediction model of mining surface deformation [13]. Marian et al. used the influence function method to predict the degree of mining-induced subsidence [14]. Li et al. established a theoretical model for predicting and analyzing subsidence in deep underground mining based on the rheology theory of rocks [8]. Yuan et al. systematically studied the influence of geological and mining conditions on the prediction parameters of probability integral method through theoretical analysis, and provided scientific basis for correctly selecting the prediction parameters of probability integral method [15]. Zhu et al., based on the traditional prediction model of probability integral method, put forward a superposition prediction method of mining subsidence in filling zone to accurately predict the mining subsidence in filling zone [16]. Yan et al. established a skewed subsidence prediction model based on the characteristics of skewed subsidence using a logarithmic normal distribution function [17]. Xing et al. predicted the dynamic surface deformation during the whole underground mining period based on probability integral method and Weibull time function [18]. Among the above methods, the probability integral method has the advantages of easy determination of parameters and strong practicability, making it widely used in various mining areas and the most commonly employed method. However, the probability integral method cannot effectively represent the movement and deformation of rock mass within the strata [19]. With the development of computer technology, people have turned theoretical prediction to numerical simulation, The main numerical simulation methods are finite element method [20, 21], boundary element method [22, 23] and discrete element method [24, 25]. Sepehri et al. used a complete three-dimensional elastic-plastic finite element model to predict land subsidence [21]. Liu et al. used 3DEC numerical simulation software to simulate the development process of mobile subsidence field from open-pit mining to full subsidence of working face, taking practical engineering as an example [26]. Guo et al. established a three-dimensional numerical simulation model of thick alluvium and thin overburden by FLAC3D software, and studied the influence of alluvial mechanical parameters on surface subsidence [27]. This paper predicted the surface subsidence caused by underground mining based on the comparison of FLAC3D numerical simulation and probability integral. The results are of great significance to control and prevent the problems caused by this subsidence.

2. The mining situation

Gequan Coal Mine is located in the west of Xingtai city, North China. Within the mining area, the altitude varies from +130 m to +195 m, resulting in a relative elevation difference of 65 m, and the geomorphic type of the mine belongs to hilly terrain. The coal-bearing strata in the mining area consist of the Middle Carboniferous Benxi Formation, Upper Carboniferous Taiyuan Formation and Lower Permian Shanxi Formation. The minable coal seams are mainly 2#, 5# and 9#. The characteristics of coal seam are as follows: 2# coal seam, commonly known as "big coal", is one of the main minable coal seams in this mine and the horizon and thickness are stable. The coal seam exhibits a vertical thickness ranging from a minimum of 1.7 m to a maximum of 3.7 m, with an average thickness of 2.7 m. The coal seam roof comprises medium-fine-grained sandstone and siltstone, while the coal seam floor consists of siltstone; 5# coal seam is located in the upper part of Taiyuan Formation, the thickness is 0.54 m to 1.41 m, with the average thickness of 1 m. The coal seam distribution is unstable and contains 0 to 2 layers of gangue, with gangue thickness ranging from 0.11 m to 0.46 m. Its structure is relatively simple and the immediate roof is composed of argillaceous sandstone and argillaceous siltstone. 9# coal seam is located at the lower part of Taiyuan formation, and it is the largest minable coal seam with the largest thickness in this well field. The thickness ranges from 3.5 m to 5.3 m, with the average thickness of 4.4 m and the coal seam is stable and minable. Its structure is complex, containing 1 to 4 layers of gangue, of which the thickness is 0.06 m to 0.26 m. The roof of coal seam 9# consists of sandy mudstone, while the floor is composed of fine sandstone and aluminous sandy mudstone.

3. The research methods

3.1 The Probability Integral Method

The probability integral method is simple and fast in calculation. Compared with large-scale prediction, it can save a lot of time and cost, and it is easier to realize calculation. It is the most important

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mining subsidence prediction method specified in the “Regulations for the Setting-up of Coal Pillars and the Mining of Pressure Coal in Buildings, Water Bodies, Railways and Main Roadways” in China.

The probability integral method considers rock formations as composed of a large number of loose granular media. Through the application of stochastic media theory, the movement of rock formations is studied as a random process following statistical laws when investigating the displacement of rock formations and surface movements. According to stochastic media theory, the surface subsidence caused by unit mining forms a normal distribution, consistent with the distribution of probability density [28]. The subsidence profile equation caused by mining can be expressed as the integral formula of probability density function. Its subsidence curve is shown in Figures 1 and 2 [15, 29].

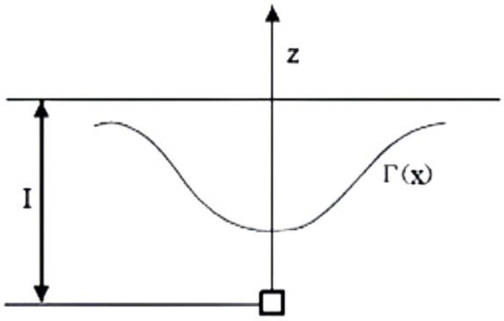

Figure 1: The subsidence curve of element basin.

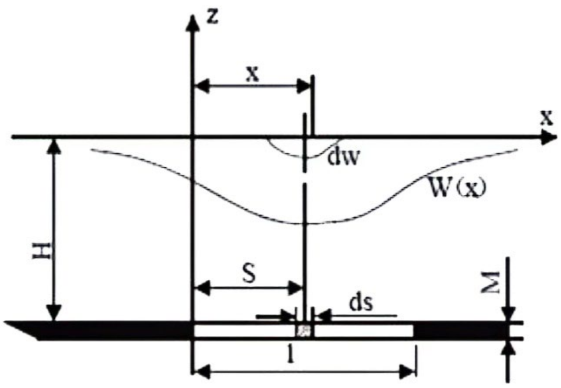

Figure 2: The surface subsidence curve of arbitrary mining unit.

The deposition formula can be expressed as:

$$W(x,y) = W_{max}C_xC_y \tag{1}$$

Where Wmax, Cx, Cy are represented by equations (2), (3), (4), respectively:

$$W_{max} = m\eta cos\alpha \tag{2}$$

$$C_x = \frac{1}{\pi}\int_{\frac{\sqrt{\pi}}{r}(x-l)}^{\frac{\sqrt{\pi}}{r}x} e^{-\lambda^2}d\lambda \tag{3}$$

$$C_y = \frac{1}{\pi}\int_{\frac{\sqrt{\pi}}{r_2}(y-l)}^{\frac{\sqrt{\pi}}{r_1}y} e^{-\lambda^2}d\lambda \tag{4}$$

Where m is the thickness of coal seam; η is the sinking coefficient; α is the inclination of the coal seam; l is the mining width along the coal seam strike; l is the mining width along the inclination of coal seam; r is the mainly influence radius of coal seam direction, r=H/tanβ; tanβ is the mainly affects the tangent of an Angle; H is the average depth of mining; r_1 and r_2 are the main influencing radii of the direction of layer uphill and downhill respectively.

3.2 The Numerical simulation method

In this paper, FLAC3D numerical simulation method was used. FLAC3D software contains 11

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constitutive models of elastic-plastic materials, and has many models. It can simulate the plastic flow or failure characteristics of geological materials when they reach the strength limit. Compared with the probability integral method, the software does not need hypothesis, nor need to measure complex key coefficients, and can visually represent the displacement and deformation of the rock strata. It can be used to simulate the law of rock mass failure and movement and deformation caused by coal mining. The simulation calculation of coal mining subsidence under complex geological mining conditions has advantages that traditional methods do not have [27, 30].

3.2.1 The boundary of model

All the scientific problems involved in mining are limited by some factors in certain external conditions. The size and direction of these factors often become the decisive factors to solve these problems. Therefore, the boundary setting must be done when building the model. Due to the coal seam studied by the model is located in the infinite crustal plane and influenced by the strata at its boundaries, the model can be constrained to deform to 0 in the positive and negative directions of the X-axis, 0 in the positive and negative directions of the Y-axis, and 0 in the negative direction of the z-axis, and the positive direction of the z-axis is not constrained, allowing for free deformation. In practical work, it is always subjected to the gravitational force within a gravitational field. Therefore, when performing calculations, it is necessary to apply the effect of gravity.

3.2.2 Main mechanical parameters

The construction of the model and the correct selection of rock mechanics parameters are the guarantee of the accuracy of solving practical engineering problems with FLAC3D. The practical problems of simulated mining must start from simplified models, and these models must obey a certain mechanical criterion before they can be calculated and solved. According to borehole data and experimental data in relevant reports, physical and mechanical parameters of each rock mass are given, as shown in Table 1.

Table 1: Physical and mechanical parameters of rock mass.

Mine	Thickness (m)	Cohesion c(GPa)	Friction ψ(°)	Density (kg/m^3)	Elasticity modulus E(MPa)	Poisson ratio u
Siltstone	53.7	4.8	40	2590	2.11	0.35
Medium Sandstone	42.7	8.0	45	2620	3.50	0.34
2# coal seam	2.7	7.5	28	1460	0.40	0.32
Siltstone	4	4.8	40	2590	2.11	0.35
Medium Sandstone	70.3	8.0	45	2620	5.40	0.34
Mudstone	3	2.8	38.95	2840	3.61	0.30
5# coal seam	1	2.17	18.8	1430	2.80	0.25
Limestone	55.5	16	44	2680	6.82	0.28
Mudstone	3.5	1.9	31.43	2699	6.38	0.30
9# coal seam	4.4	2.0	35	1600	0.80	0.38
Siltstone	13	4.3	40	2650	5.00	0.35
Limestone	9	15.4	44	2680	8.50	0.26

Note: Data are from coal mine production report.

3.2.3 Establishment of the model

The average mining depth of 2# coal seam is 170 m and the mining thickness is 2.7 m. The average mining depth of 5# coal seam is 250 m and the mining thickness is 1.0 m. The average mining depth of 9# coal seam is 310 m and the mining thickness is 4.4 m. The roof is applied to the top of the model according to the equivalent load. The equivalent load is calculated according to the following formula:

$$q = \sum h\rho g \tag{5}$$

Where, q is equivalent load; h is the thickness of unsimulated coal seam; ρ is the density of unsimulated coal seam; g is gravitational acceleration.

Because the research is on underground coal mining, it can be solved by building model with brick, which is commonly used in mining engineering with FLAC3D. According to the analysis of practical problems in Gequan Coal Mine, the model chooses the coal seam strike as the Y-axis direction, with a length of 1200 m; The X-axis represents the direction of the coal seam dip, with a length of 500 m; The Z-axis represents the vertical direction, with a height of 400 m. The model consists of 232806 nodes and

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21600 tetrahedral elements and the plastic failure criterion of the paraboloid Moore-Kulun is selected to simulate the working face. Considering the boundary benefit, four times the width of the roadway is reserved at both ends as the transition area. The initial model is shown in Figure 3.

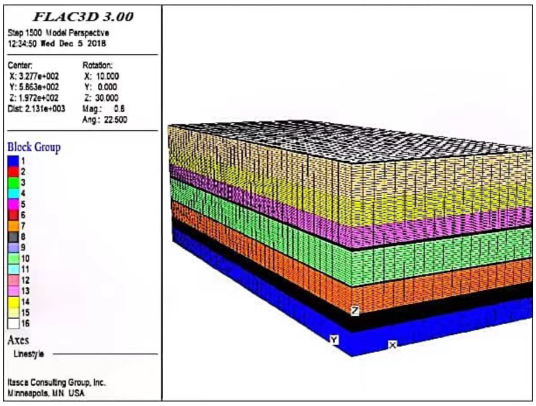

Figure 3: The schematic diagram of the model.

4. Results and discussion

4.1 The calculation results of probability integral

(1) Determination of the geological and mining technical conditions of Gequan coal mine

Mining Depths: 2# coal seam with 170 m, 5# coal seam with 250 m, 9# coal seam with 310 m. Coal Seam Thicknesses: 2# coal seam with 2.7 m, 5# coal seam with 1.0 m, 9# coal seam with 4.4 m. Workface Length: 1200 m. Inclined Length: 100 m.

(2) Determination the parameters of the surface movement

Based on the tested data, actual situation, regional experience and relevant specifications, the calculation parameters are given in Table 2.

Table 2: Calculation parameters of probability integral.

Subsidence coefficient q	Mainly affects tangent angles $\tan\beta$	Influence Angle of mining propagation θ/ (°)	Horizontal displacement coefficient b	Recovery rate c/ (%)
0.88	2	79.8	0.25	85

(3) Calculation of the Maximum Surface Movement and Deformation by the Maximum Formula of Semi-infinite Mining

Subsidence: $W_{0m}=q_m=6.06$ m;

Tilt amount: $i_{0m}=W_{0m}/r=39.1$ mm/m, At x/r=0, i.e. x=0;

The curvature: $K_{0m}=0.38*10-3/m$;

Horizontal distance: $U_{0m}=bW_0=1.51$ m;

Horizontal deformation: $\varepsilon_{0m}=\pm1.52bi_0=\pm14.858$ mm/m.

4.2 The results of numerical simulation

The overlying soil and rock mass above the goaf loses support because of the underground coal seam being mined out, resulting in the redistribution of stress within the soil and rock mass. The area adjacent to the coal pillar becomes a zone of increased pressure, where the soil and rock mass in this area are damaged by compression [31]. Therefore, the initial stress balance simulation must be carried out before the simulated excavation. The simulation results are shown in Figure 4.

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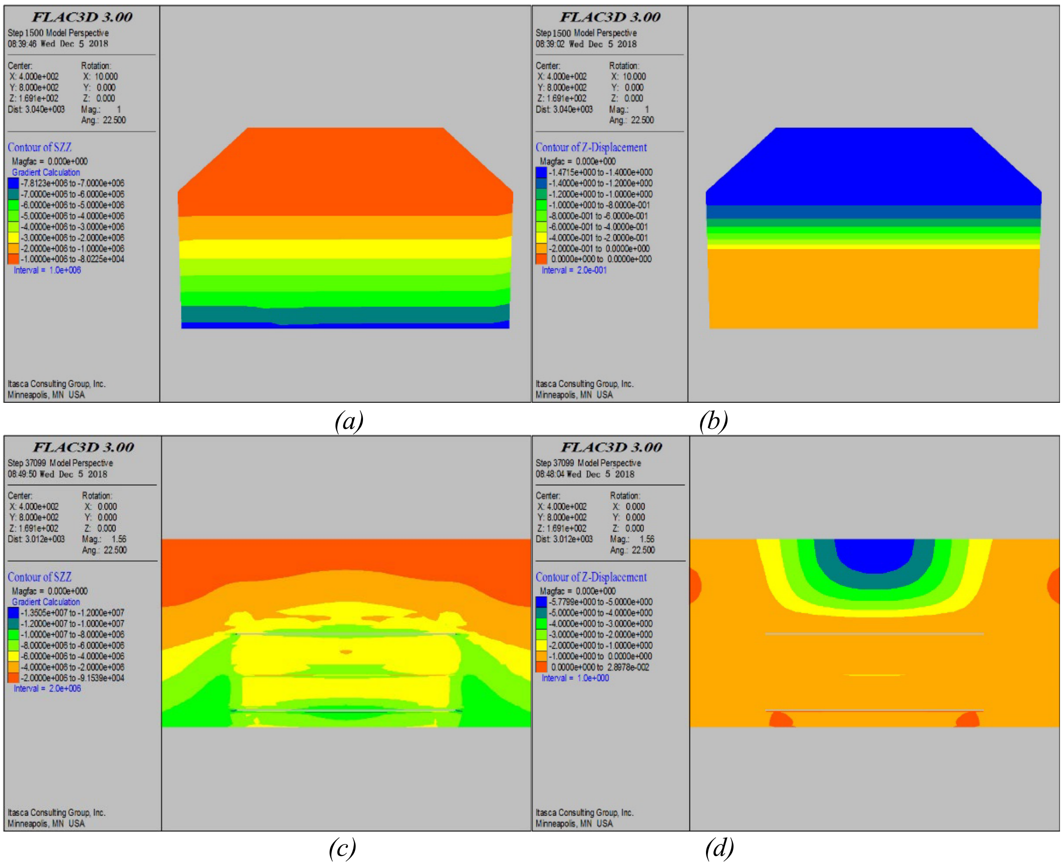

Figure 4: (a) The nephogram of initial stress; (b) The vertical displacement diagram of initial stress; (c) Vertical stress distribution map of section; (d) Surface subsidence map after mining.

From the comparison of Figure 4(a) and Figure 4(c), it can be seen that the stress in the vertical direction is mainly determined by the physical and mechanical properties of itself and the overlying strata. Before excavation, it is in a stable state due to long-term geological action; After excavation, it will destroy the stress balance of surrounding strata and cause the phenomenon of the stress redistribution. The stress of overlying strata in goaf decreases gradually from bottom to top, and the stress is maximum at both ends of goaf. As can be seen from Figure 4(b) and Figure 4(d), before excavation, the strata have uniform settlement. After excavation, uneven subsidence occurs in a certain range due to the change of stress. The subsidence value gradually decreases from bottom to top above the goaf, and gradually decreases from excavation center to both ends on the surface. And the maximum subsidence value is 5.77 m.

4.3 Comparative analysis of calculation results

The results of probability integral theory and FLAC3D numerical simulation were compared and analyzed, as shown in Table 3.

Table 3: Comparative Analysis.

Methods	The maximum subsidence value(m)
The Probabilistic Integral Method	6.06
The Numerical simulation method	5.77
Actual value of surface subsidence monitoring	(5.9-6.2)

According to the data in the table, the result of probability integral calculation is slightly larger than that of numerical simulation. This is because the weak strata above the coal seam is relatively thin, which is prone to inadequate mining, and the probabilistic integral method will be affected; at the same time, for the excavation of multiple layers of coal seams, the probability integration method often fails to fully consider the influence between adjacent coal seams. While the numerical simulation method does not need to consider these factors, nor need to assume some complex key parameters, and the calculation results are close to the actual situation.

5. Conclusions

(1) The maximum surface subsidence value calculated by probability integral method is 6.06 m, while that calculated by numerical simulation is 5.77 m, with the former being larger than the latter. This is because when probability integral is used in multi-layer coal mining, especially in the case of inadequate mining, the theoretical calculation results are often larger than the numerical simulation. Therefore, FLAC3D numerical simulation can be used to provide more accurate prediction results in full mining and complex strata mining.

(2) The simulation results show that the closer to the goaf center, the larger the surface subsidence will be. The amount of subsidence decreases gradually from bottom to top, and from center to both ends. At the same time, the stress at both ends of goaf is the largest. This can be used to study the subsidence law caused by the ground after mining and use the land in the safest way.

(3) Since the propellant of the new working face will have a certain impact on the surrounding goaf, the influence of the nearby goaf must be considered in the later underground mining. At the same time, the goaf should be maintained and strengthened to improve the stability of the goaf.

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