Study on Mining Subsidence of Mineral Deposit and Overburden Stability Based on Probability Density Function

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Abstract. Mining subsidence, a major geological disaster caused by underground mining, will seriously damage the land. In this paper, the author predicts the surface subsidence in mining subsidence area of certain mineral deposits and strata condition by applying the Probability Density Function Method, and designs two evaluation schemes for calculation of the overlying rock formation stability. Study results provide a reliable basis for the disastrous governance of mining subsidence in mining areas.

1. Introduction
Surface deformation in mining areas is one of the major artificial geological disasters, and surface movement and deformation will damage the ecological environment, surface buildings (structures), water body, land, etc. to certain extent. In fact, the surface deformation is the movement and deformation of rock formation in essence, indicating that the surface movement and deformation affected by mining is exactly the same as rock formation movement and deformation. Therefore, study on the law and prediction of surface deformation is of much concern to the exploration of the movement law of overlying rock, mechanical properties of rock mass, and related influence factor(s). Surface movement law varies depending on different geological conditions and mining technologies and methods in different areas. To further study on surface deformation law of deep mining and explore the influence of changes in mechanical properties of overburden exploitation on the surface deformation, this paper analyzes the surface deformation law of deep mining by applying the measured data of surface movement and deformation on mining subsidence of mineral deposit in an iron mine deposit in a certain place.

2. Model for Calculation of Overburden Movement and Deformation

2.1. Vertical Movement Model of Overburden
As a randomly cutoff granular media, it can be abstracted as the theoretical model in Figure 1 when its movement law is studied:
The probability of loose body movement within any square (i,k) in Figure 1 can be obtained by applying the inductive method:

\[ P(i, k) = \left( \frac{1}{4} \right)^k C_{2k}^{i+k} \]  

(1)

Where, C is the mathematical combination notation and i,k is the coordinate value of the square.

According to De Moiver-Laplace theorem, the following formula can be obtained when 2k is large enough:

\[ \lim_{k \to \infty} P(i, k) \approx \frac{1}{\sqrt{\pi k}} e^{-\frac{i^2}{2k}} \]  

(2)

Giving that the square is small enough and media divided by square are recorded as continuum, the model’s probability density function of loose body movement is below when x=i, z=k:

\[ f(x, z) \approx \frac{1}{\sqrt{2\pi \sigma(z)}} e^{-\frac{x^2}{2\sigma^2(z)}} \]  

(3)

It can be considered that the subsidence probability density function of overburden exploitation is subject to the normal distribution of N(0, \sigma^2(z)) in ideal state.

For any rock formation affected by mining, the basic form of the subsidence probability density function is exactly the same but only the variance of model parameter is different from each other. In terms of the value of two-dimensional surface subsidence, it can be assumed that Z_i=H_0. When the distance from the surface point to the lower stope is X ≥ 3\sigma(H_0), the subsidence probability is obtained as follows:

\[ P\{X \geq 3\sigma(H_0)\}1 - \Phi(3) = 0.00135 \]  

(4)

Thus obtained that the movement probability of overburden affected by mining located beyond 3\sigma(H_0) is only 0.135% of the total. Therefore, it can be considered from an engineering perspective that the overburden located beyond 3\sigma(H_0) will not be affected by mining. The point corresponding to 3\sigma(H_0) is the boundary point affected by mining. The radius of internal overburden affected by mining at any formation can be expressed as follows when R_0=3\sigma(H_0):

\[ R_i = \frac{H_0}{tg \delta_0} \left( \frac{Z_1}{H_0} \right)^n \]  

(5)

In the above formula, H_0 is the mining depth, R_0 is the radius affected by mining, \delta_0 is the boundary angle affected by mining, and n is the parameter related to the properties of overburden.

### 2.2 Calculation of Parameters of Subsidence Probability Density Function

The model parameter should be calculated by applying the boundary angle parameter that is the intersection angle which is formed by the connecting line from the subsidence point of 10mm on the main section of surface movement basin to the mining boundary and the horizontal line on the pillar side under full mining, as shown in Figure 2.
The boundary angle is related to the geological mining factors including the properties of overburden, exploitation degree, mining degree, and mining thickness, etc. The boundary angle in strike direction $\delta_0$ changes a little in each single ore bed of mining, and the variation with depth ratio should be taken into consideration in multiple ore beds of mining. The relationship between boundary angle in strike direction and depth ratio under full mining by longwall collapse method in mining areas is:

$$\delta_0 = 57.6^\circ + 0.078 \frac{H}{M}$$

In the above formula, $H$ is the mining depth and $M$ is the mining thickness.

2.3. Calculation of Basin Subsidence and Deformation in Rectangular Stope

Based on the probability density function of mining rock formation and surface subsidence in horizontal ore bed, the calculation formulas of surface subsidence and deformation on the main section of semi-infinite mining in strike direction are established as follows:

1. Subsidence

$$W(x) = W_{\text{max}} \left( \int_0^{3x} \frac{1}{\sqrt{2\pi R_0^2}} e^{-\frac{\lambda^2}{2R_0^2}} d\lambda + \int_{3x}^{+\infty} \frac{1}{\sqrt{2\pi R_0^2}} e^{-\frac{\lambda^2}{2R_0^2}} d\lambda \right)$$

2. Tilting

$$i(x) = \frac{dW(x)}{dx} = \frac{3W_{\text{max}}}{\sqrt{2\pi R_0^2}} e^{-\frac{9x^2}{2R_0^2}}$$

3. Curvature

$$K(x) = \frac{d^2W(x)}{dx^2} = \frac{27}{\sqrt{2\pi R_0^2}} \frac{W_{\text{max}}}{R_0} \left( \frac{x}{R_0} \right) e^{-\frac{9x^2}{2R_0^2}}$$

4. Horizontal Movement

$$U(x) = b \times R_0 \times i(x)$$

5. Horizontal Deformation

$$\varepsilon(x) \frac{dU(x)}{dx} = b \times R_0 \times K(x)$$

3. Classification Standards of Damage Grade of Buildings

The damage degree of buildings affected by mining depends on the value of surface deformation and the ability of building to resist deformation. With reference to relevant standards, damage grades of urban buildings are classified as follows shown in Table 1.
Table 1. Classification of Damage Grade of Brick-concrete Structure Buildings.

| Damage Grade | Value of Surface Deformation | Damage Classification | Treatment Method         |
|--------------|-------------------------------|-----------------------|--------------------------|
|              | Horizontal Deformation \(\varepsilon\) (mm/m) | Curvature \(K(10^{-3}/m)\) | Tilting \(i (mm/m)\) |
| I            | \(\leq 2.0\)                  | \(\leq 0.2\)          | \(\leq 0.3\)            | Slight Damage | Simple Maintenance and Repair |
| II           | \(\leq 4.0\)                  | \(\leq 0.24\)         | \(\leq 6.0\)            | Mild Treatment | Minor Repair |
| III          | \(\leq 6.0\)                  | \(\leq 0.6\)          | \(\leq 10.0\)           | Moderate Treatment | Medium Repair |
| IV           | \(>6.0\)                      | \(>0.6\)              | \(>0.6\)                | Severe Damage  | Overhaul       |

4. Prediction on Surface Movement and Deformation
In accordance with study data on strata form, thickness and tilting angle of local ore beds, the movement parameters of rock formation are selected respectively in conditions of collapse and non-collapse by strip mining, and then evaluated respectively with the thickness and tilting angle of actual ore beds in different sections.

4.1. Prediction Schemes
The mining of mineral deposit is executed in part, and its mining intensity changed with different strata forms of the ore body. The strip mining will be applied basically since its ratio of mining and remaining keeps relatively high. For areas of thin ore body, the remaining pillars keep stable, forming alternate strip empty areas; for areas of thick ore body, some irregular pillars collapse have their intensity reduced due to the high mining height and weathering and denudation, causing the penetration of adjacent mining strips followed by forming a relatively large empty area. The underground goafs extend relatively slowly in vertical direction without affecting the overlying Quaternary strata and the surface. Nevertheless, as time goes, the pillars would further experience weathering, deliquescence and denudation, which may lead to a wide puking to overflow the surface and threaten the buildings on the ground. In summary, two schemes will be taken into consideration when the surface movement and deformation are predicted, stated as follows:

a) When the strip collapse mining method is applied, the ratio of mining and remaining is designed reasonable and the remaining pillars in mining progress meet the requirements, which would not lead to a wide puking and the movement of overburden.

b) When the strip collapse mining method is applied, the ratio of mining and remaining is designed unreasonable or the remaining pillars in mining progress fail to meet the requirements, which would lead to a wide puking and the movement of overburden over time.

4.2. Selection of Calculation Parameters
The calculation parameters of overburden movement are selected and determined through comprehensive analysis according to local geological data, observation data of overburden movement in similar mines, and data of some exploration sections, as shown in Table 2.

| Scheme | q   | \(\tan \beta\) | b   | \(\theta_0\) | K   | S/H |
|--------|-----|----------------|-----|--------------|-----|-----|
| a)     | 0.06| 1.28           | 0.25| 60           | 0.55| 0.11|
| b)     | 0.18| 1.28           | 0.25| 60           | 0.55| 0.11|

4.3. Prediction on Surface Movement and Deformation
The goafs by applying the geophysical exploration method are divided into different units to be calculated according to the prediction schemes above and calculation parameters of overburden
movement by predicting the strata form of ore bed. With the calculation result, the maximum values of surface movement and deformation in two schemes are shown in Table 3.

Table 3. The Maximum Values of Surface Movement and Deformation in Each Scheme.

| Scheme | W(mm) | I (mm/m) | ε (mm/m) | K (10\(^{-3}\)/m) |
|--------|-------|----------|----------|-----------------|
|        |       | EW direction | SN direction | EW direction | SN direction | EW direction | SN direction |
| a)     | 196.77 | 1.58      | 0.79      | 1.12          | 0.70          | 0.05          | 0.02          |
| b)     | 843.52 | 8.74      | 3.48      | 3.54          | 1.92          | 0.14          | 0.05          |

According to the aforesaid result of prediction on surface movement and deformation with reference to the classification standards of damage grade of surface structures in Table 1, it can be seen that when Scheme a) is applied, the main structures on the ground are all within damage range of brick-concrete structure buildings at Grade I, inferior to damage standards at Grade I as i ≤ 3mm/m, Ε ≤ 2mm/m, and also meet the allowable deformation values of various industrial structures. When Scheme b) is applied, the damage grade caused by surface movement and deformation in some areas exceeds Grade II Damage of brick-concrete structure buildings, where the maximum value of inclination i = 8.74mm/m, reaches Grade III Damage. In terms of horizontal deformation, the maximum value, Ε = 3.54mm/m, reaches Grade II Damage.

5. Conclusion

Based on the iron ore geology and mining conditions in a certain place, the model for calculation of overburden movement and deformation affected by mining is determined by applying probability density function. Then the model parameters are calculated in combination with the boundary angle theory. With the calculation model as the probability density function of mining rock formation and surface subsidence in horizontal ore bed, the prediction formulas of surface subsidence and deformation on the main section of semi-infinite mining in strike direction are established for designing two prediction schemes by applying strip mining to the pillars in conditions of collapse generated stably and unsteadily, followed by the calculation of the surface movement and deformation. Overall, these results provide a theoretical basis for the safety and stability evaluation of surface buildings.

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