Research Article

Geological Structural Surface Evaluation Model Based on Unascertained Measure

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The surrounding rock structure plane survey is the basis for mine geological structure evaluation and stability of surrounding rock. On the basis of the unascertained measurement theory and scanline method, the surrounding rock stability of the underground geological structure plane in Lingbao Luoshan Gold Mine is evaluated. First, according to the structural plane five grading standards, the 9 single-index measure functions are constructed. Second, the information entropy is used to determine the weight of each indicator. Accordingly, a multi-index comprehensive measure evaluation vector is established. Finally, the confidence level is used to determine the structural plane stability level. Results show that surrounding rock grades of middle sections of \( R_1 \), \( R_2 \), and \( R_3 \) are Grades III, IV, and IV in Lingbao Luoshan Gold Mine, respectively. The evaluation grade is consistent with the actual situation of the mine, and strengthening the surrounding rock support for the middle sections of \( R_2 \) and \( R_3 \) is necessary. According to engineering practice, the evaluation model of the underground structure of metal mines established in this study has a practical value.

1. Introduction

The structural plane survey is the basis for understanding the geological structure, geostress analysis, and surrounding rock stability evaluation of mining areas. The structural face is a discontinuous surface with low or no tensile strength, including all geological separation surfaces. Different structural planes have different mechanical properties and scales, and common structural planes are divided into fractures, cleavage, unconformity, and folds. Rock mass discontinuity is caused by the existence of joints (faults, joints, and folds). On the one hand, when the rock mass is relatively complete, it can be analyzed by using the mechanical method of continuous media. On the other hand, when the rock mass has good integrity, it can be analyzed by using the mechanical method of the continuous medium. However, the majority of rock masses are discontinuous bodies formed by cutting the plurality of structural planes and has anisotropy. The structural surface can be used to reflect the geological structure within the area because its presence reduces the strength of the rock mass. Soft mud and weak surface in the interlayer often cause remarkable harm in engineering [1] (as shown in Figure 1). Hence, investigating and analyzing structural planes in engineering are often necessary.

According to the classification standard of engineering rock mass, the structural plane scale is divided into five grades. The length of structural planes I, II, and III is several tens or even hundreds of meters and directly affects the stability of the entire engineering rock mass. Grades IV and V are mainly statistical structural planes. A structural plane
Figure 1: Collapsed highway slope.

destroys the rock mass integrity and affects the physical-mechanical properties and stress distribution state. The distribution of structural planes IV and V is random. Hence, statistical methods are needed to investigate the structural plane. Common survey methods include statistical window, borehole lithology, and scanline [2, 3]. Zhao et al. [4] used a detailed scanline method to investigate the structural plane of tungsten mines. García-Luna et al. [5] applied digital camera technology to structural surface analysis, thereby providing a new idea for structural surface investigation. As the distribution of structural planes is affected by many factors, randomness and uncertainty exist in its distribution. Therefore, Hekmatnejad et al. [6] evaluated the methods of statistical analysis of joint length and distribution utilization probability. Yang et al. [7] estimated the length and distribution of the joints by using the probabilistic method.

The engineering rock mass classification standards commonly used in engineering mainly adopt the RMR classification [8] method and the Q classification method [9]. The RMR classification method is the uniaxial compressive strength (P1), rock quality index (P2), joint spacing (P3), joint condition (P4), groundwater condition (P5) of the rock block, and the orientation and foundation according to the joint plane, and the edge. The correction coefficient (P6) determined by the between the slope and the cavity is six signals as basic boundaries. According to the condition of the rock mass, the RMR total score of the rock mass quality can be obtained by scoring and adding one by one. With more influencing, such as groundwater, blast damage, stress changes, and other effects on the stability of surrounding rock, it is necessary to improve the RMR classification method. Barton et al. [9] proposed the Q grading method is based on the full strength of the rock, the shear strength of the chimeric rock mass, and the active stress product of the surrounding rock. Neither of these methods considers many uncertainties in the stability evaluation of surrounding rock. Uncertain measures can solve the uncertain reasons in the evaluation problem. The quantitative signals are used for analysis, and the weight of each is considered. Reduce the error of people’s subjective evaluation. The unascertained mathematical theory established by Liu et al. [10] was based on the unascertained information and mathematical processing proposed by Professor Wang Guangyuan [11] in his earlier days. Unascertained information is defined as indeterminate information that is different from fuzzy, random, and gray information [12–14]. Unascertained measure theory is widely used in risk assessment in fields, such as slope risk assessment, urban environmental assessment, underground goaf collapse, enterprise innovation capability evaluation, and coal mine safety assessment [15–17].

In this study, on the basis of the unascertained measure theory, influencing factors and grading standards are determined based on the survey scanline structure and engineering rock mass grading standards. Influencing factors mainly include structural surface lithology, rock quality designation, rock integrity coefficient, joint mean track length, joint occurrence, joint spacing, joint roughness, joint opening degree, and water seepage on the rock surface. We investigate the structural plane by using the scanline method in the three production middle sections of Luoshan Gold Mine located in Lingbao City. This study establishes a single-indicator measure function and uses information entropy [18] to determine the weight of each indicator first. A multi-indicator measure function is then established. Finally, the confidence criteria to analyze the results are used. Research shows that the unascertained measure theory is suitable for structural plane evaluation. A new method is proposed for evaluating the stability of surrounding rock and performing support measures.

2. Unascertained Measure Theory

When evaluation influencing factors exist in an evaluation object, these factors are recorded as \( X_1, X_2, X_3, \ldots, X_n \), and the survey evaluation space is recorded as \( X = \{ X_1, X_2, \ldots, X_n \} \). Each evaluation factor includes an \( m \) evaluation index, and the index space is recorded as \( I = \{ I_1, I_2, \ldots, I_m \} \). \( x_{ij} \) represents the evaluation value of the \( j \)th indicator of the \( i \)th evaluation influencing factor. \( p \) levels exist in \( x_{ij} \), and \( C_k \) is the evaluation level \( k \) as \( C_k (k = 1, 2, \ldots, p) \). If the \( k \)th level is stronger than the \( k + 1 \)th level, then this lever is recorded as \( C_k > C_{k+1} \). If \( C_1 > C_2 > \cdots > C_p \), then \( \{ C_1, C_2, \ldots, C_m \} \) is an ordered segmentation class of the evaluation space \( U \).

2.1. Single-Index Unascertained Measure. If \( u_{ijk} = u \left( x_{ij} \in C_k \right) \) represents the degree to which the observed value \( x_{ij} \) belongs to the \( k \)th evaluation level \( C_k \), and it satisfies boundedness, normality, and additivity, then it can be expressed as the following relationship:

\[
0 \leq u \left( x_{ij} \in C_k \right) \leq 1, 
\]

\[
u \left( x_{ij} \in U \right) = 1, 
\]

\[
u \left( x_{ij} \in U \cap C_j \right) = \sum_{l=1}^{k} u_{lj} \left( x_{ij} \in C_l \right),
\]

where \( u \) is the unascertained degree that is generally referred to as the measure. If \( u \) fails to satisfy Formulas
(1) to (3), then the value of \( u \) cannot guarantee its correctness. \( u_{ij,k} \) is a single-index evaluation matrix that uses a linear unascertained measure function and can be expressed as

\[
(u_{ij,k})_{n \times p} = \begin{bmatrix}
  u_{i11} & u_{i12} & \cdots & u_{i1p} \\
  u_{i21} & u_{i22} & \cdots & u_{i2p} \\
  \vdots & \vdots & \ddots & \vdots \\
  u_{in1} & u_{in2} & \cdots & u_{inp}
\end{bmatrix}.
\]  

(4)

2.2. Determining the Weight of Indicators. Let \( w_j \) be the weight of \( X_j \), and \( w_j \) denotes the relative importance degree of the measurement index \( x_{ij} \) compared with other indicators. \( 0 \leq w_j \leq 1 \), \( \sum_{j=1}^{m} w_j = 1 \), where \( w = \{w_1, w_2, \ldots, w_m\} \) is called the index weight vector. By using the information entropy [16] theory to determine the index weight, we obtain

\[
v_j = 1 + \frac{1}{\ln p} \sum_{k=1}^{p} u_{jk} \ln u_{jk},
\]  

(5)

\[
w_j = \frac{v_j}{\sum_{i=1}^{n} v_i}.
\]  

(6)

As the evaluation matrix of a single-index measure is known, the weight \( w_j \) of each index can be obtained by using Formulas (5) and (6).

2.3. Multi-Index Comprehensive Measure Evaluation Vector. If \( u = u_0 \) (\( R \in C_k \)) indicates the degree to which the evaluation target \( R \) belongs to the \( k \)th evaluation level, then

\[
u_{jk} = \sum_{i=1}^{n} w_j u_{ijk},
\]  

(7)

where \( w_j \) is the weight of the indicator \( I_j \) that satisfies

\[
0 \leq w_j \leq 1,
\]  

(8)

\[
\sum_{j=1}^{m} w_j = 1.
\]

\( u_{jk} \) satisfies the following relationships:

\[
0 \leq u_{jk} \leq 1,
\]  

(9)

\[
\sum_{k=1}^{p} u_{jk} = 1.
\]

(10)

2.4. Confidence Recognition Criteria. Use the confidence recognition criteria, confidence \( \lambda \) (normally \( \lambda = 0.6 \) or \( 0.7 \)), for the sequence \( C_1 > C_2 > \cdots > C_p \), to satisfy the following formula:

\[
k_o = \min \left\{ k : \sum_{i=1}^{k} u_i > \lambda, \ k = 1, 2, \cdots, p \right\}.
\]  

(10)

Then, the evaluation object belongs to the \( k_o \) evaluation level grade \( C_k \).

3. Steps in the Structural Surface Evaluation Analysis Based on Unascertained Measure

(1) Determine the influencing factors and classification criteria for structural surface evaluation. The main influencing factors of structural plane survey based on the scanline method include lithology, rock quality designation, rock integrity, joint track length, joint occurrence, fracture roughness, joint opening degree, and rock moisture content.

(2) Determine the single-index unascertained measure function of the structural plane evaluation according to the grading standard.

(3) Determine the evaluation matrix according to measured structural surface indicators and the single unascertained measure function.

(4) By using information entropy to determine the weight of the evaluation index, the multi-index measure evaluation vector is obtained via Formula (7).

(5) Evaluate the structural plane level by using the confidence criteria.

4. Case Study

The Luoshan Gold Mine at Lingbao City is located in the Xiaoqinling District in the southern margin of the North China Platform. The lithology of the mining area is mainly composed of black cloud slanted gneiss, mixed gneiss, and mixed granite. Fault structures are well developed in the mining area. An ore-controlling structure is a set of ductile shear zones and faults that are distributed near the east-west direction. This structure generally occurs near the east-west direction and slightly inclined to the north. The majority of inclination angles are gently inclined between 30° and 40° with a few steeply reaching 60°.

Gold ore bodies, produced in ductile shear zones and faults, are strictly controlled by fault structures. The main surrounding rock is composed of fragmented mixed granite. In recent years, the frequent occurrence of ground pressure activities is caused by the formation of a large number of goafs via stratified caving. Mining pressure activities remarkably threatens the safety of mining workers. Mining methods need to be optimized to ensure safe production in mines.
Structural planes of the three middle operations (R1, R2, and R3) are evaluated from top to bottom. Sections R1 and R3 are mainly composed of mixed granite, and section R2 is mixed with gneiss.

4.1. Structural Surface Evaluation Indicators and Grading Standards. Line surveying method is mainly used for statistical investigation of microstructural planes of Grades IV and V. Based on investigation and experimental results, the rock uniaxial compressive strength Rc, engineering rock quality index RQD, rock integrity coefficient Kv, joint trace length L, and joint occurrence (strike angle θ1 and dip angle θ2), where θ1 and θ2 are calculated by using the dominant structural plane, and strike angle θ1 represents the strike difference between joint and roadway), fracture roughness coefficient JCR, joint opening degree B, and rock moisture content ω are the main parameters that represent the rock mass quality. According to the engineering rock mass quality grading standards [19], Table 1 lists the structural surface grading standards. Table 2 presents the parameters of each middle section.

4.2. Single-Index Measure Function Model. On the basis of the evaluation criteria of the rock structural plane, the single-index measure function of uniaxial compressive strength Rc, rock quality designation RQD, rock integrity coefficient Kv, joint trace length L, joint occurrence (strike θ1 and dip angle θ2), fracture roughness coefficient JCR, joint opening degree B, and rock moisture content ω was established as shown in Figures 2–10.

The parameters in Table 2 show that the evaluation matrix of each middle section is obtained from the graph. Taking middle section R1 as an example, the evaluation matrix is calculated as follows:

\[
(u_{1jk})_{9\times5} = \begin{bmatrix}
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0.6 & 0.4 & 0 \\
0 & 0 & 0.75 & 0.25 & 0 \\
0 & 0.875 & 0.125 & 0 & 0 \\
0 & 0 & 0 & 0.4 & 0.6 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0.231 & 0.769 & 0 \\
0.25 & 0.75 & 0 & 0 & 0 \\
\end{bmatrix}
\]  

4.3. Multi-Index Comprehensive Measure Evaluation Vector. Information entropy is used to determine the weight of each indicator. From Equations (5) and (6), the weight vector of middle section R1 is \( W = \{0.145, 0.145, 0.084, 0.094, 0.111, 0.084, 0.145, 0.096, 0.094\} \). The specific calculation process is as follows:

- \( v_1 = v_2 = v_7 = 1 + \frac{1}{\lg 5} (1 \lg 1 + 0) = 1 \),
- \( v_4 = v_6 = 1 + \frac{1}{\lg 5} (0.6 \lg 0.6 + 0.4 \lg 0.4) = 0.582 \),
- \( v_3 = 1 + \frac{1}{\lg 5} (0.75 \lg 0.75 + 0.25 \lg 0.25) = 0.651 \),
- \( v_5 = 1 + \frac{1}{\lg 5} (0.875 \lg 0.2 + 0.125 \lg 0.125) = 0.766 \),
- \( v_9 = 1 + \frac{1}{\lg 5} (0.231 \lg 0.231 + 0.769 \lg 0.769) = 0.664 \),
- \( v = v_1 + v_2 + v_3 + v_4 + v_5 + v_6 + v_7 + v_8 + v_9 = 6.896 \),
- \( w_1 = w_2 = w_7 = \frac{v_1}{v} = \frac{1}{6.896} = 0.145 \),
- \( w_3 = w_6 = \frac{v_3}{v} = 0.582 \),
- \( w_4 = w_8 = \frac{v_4}{v} = 0.651 \),
- \( w_5 = \frac{v_5}{v} = 0.766 \),
- \( w_8 = \frac{v_8}{v} = 0.664 \),

The multi-index comprehensive measure evaluation vector of the middle segment of R1 can be obtained from the weight vector W and Formula (11) as follows:

\[
\text{ui} = \{0.024, 0.313, 0.302, 0.165, 0.195\}.
\]

4.4. Evaluation Result Analyses. The confidence is introduced in this section to evaluate the result with a confidence value of \( \lambda = 0.6 \). From the multi-index comprehensive evaluation vector and confidence criterion evaluation, \( k_0 = 0.024 + 0.313 + 0.302 = 0.639 > \lambda \) exist from large to small, and the structural plane evaluation level of middle section R1 is Grade III. However, \( k_0 = 0.195 + 0.165 + 0.302 = 0.679 > \lambda \) exist from small to large, and the evaluation level is also Grade III. Therefore, the two judgment results are consistent, and the structural plane evaluation level of the R1 middle section is Grade III.

Similarly, the same method is used to evaluate the middle sections of R2 and R3, and the surrounding rock stability evaluation results of the middle sections of R2 and R3 are all Grade IV.

From an overall view of the three middle sections, the entire area of the mining area is mainly composed of mixed granite, and the rock is broken. Joints with a trace dominant length of approximately 1 m and the dominant occurrence that substantially differs from the roadway direction have a major impact on the surrounding rock stability. These features are the main reason for the poor evaluation of the structural surface. Other major factors affecting the structural plane include lithology, rock integrity, joint trace length, and joint occurrence.
Looking at the relevant data of the mine, the rock in middle section $R_1$ is relatively dry, and the roadway surface in middle sections $R_2$ and $R_3$ is mildly to severely wet. The groundwater of middle section $R_1$ penetrates along the joint surface and into middle sections $R_2$ and $R_3$ because middle sections $R_2$ and $R_3$ are mined. A large amount of groundwater weakens the strength and reduces the stability of surrounding rock, making the surrounding rock in middle sections $R_2$ and $R_3$ vulnerable to failure. Therefore, strengthening the support of middle sections $R_2$ and $R_3$ and improving the hydrophobic drainage of the lower middle section in time are necessary. The design of the main transportation

### Table 1: Structural plane evaluation classification standard.

| Influencing factor indicator         | I grade ($C_1$) | II grade ($C_2$) | III grade ($C_3$) | IV grade ($C_4$) | V grade ($C_5$) |
|--------------------------------------|----------------|-----------------|------------------|-----------------|----------------|
| Uniaxial compressive strength $R_c$ (MPa) | >150           | 150~120         | 120~80           | 80~30           | 30~0           |
| Rock quality designation $RQD$ (%)  | 100~90         | 90~80           | 80~60            | 60~30           | 30~0           |
| Rock integrity coefficient $K_v$    | 0.75~1         | 0.55~0.75       | 0.35~0.55        | 0.15~0.35       | 0~0.15         |
| Joint trace length $L$ (m)          | 0~0.3          | 0.3~0.5         | 0.5~0.8          | 0.8~1.2         | 1.2~1.5        |
| Strike $\theta_1$ (°)               | 90~75          | 75~60           | 60~45            | 45~30           | 30~0           |
| Dip angle $\theta_2$ (°)            | 0~30           | 30~45           | 45~60            | 60~75           | 75~90          |
| Fracture roughness coefficient $JCR$| 20~12          | 12~8            | 8~4              | 2~4             | 2~0            |
| Joint opening degree $B$ (mm)       | 0~0.2          | 0.2~1.0         | 1.0~2.0          | 2.0~5.0         | >5             |
| Rock moisture content $\omega$ (%)  | 0~20           | 20~30           | 30~45            | 45~65           | 65~100         |

### Table 2: The middle section structural surface parameters.

| Middle section | $R_c$ (MPa) | $RQD$ (%) | $K_v$ | $L$ (m) | $\theta_1$ (°) | $\theta_2$ (°) | $JCR$ | $B$ (mm) | $\omega$ (%) |
|----------------|-------------|-----------|-------|--------|----------------|----------------|-------|----------|-------------|
| $R_1$          | 120         | 25        | 0.37  | 0.7    | 54             | 66             | 8     | 1.2      | 26          |
| $R_2$          | 95          | 35        | 0.33  | 0.8    | 67             | 72             | 6.5   | 2        | 43          |
| $R_3$          | 100         | 28        | 0.20  | 1.1    | 43             | 63             | 5     | 2.5      | 58          |

$$\text{FIGURE 2: Uncertainty measurement function of } R_c.$$  
$$\text{FIGURE 3: Uncertainty measurement function of } RQD.$$  
$$\text{FIGURE 4: Uncertainty measurement function of rock integrality coefficient.}$$  
$$\text{FIGURE 5: Uncertainty measurement function of joint trace length.}$$
lane direction should be kept as small as possible considering the dominant surface of the structural plane to avoid wider damage areas.

5. Conclusion

(1) On the basis of the structural plane investigation via the scanline method, the evaluation factors and grading standards of the structural plane are determined. Quantitative analysis of the evaluation by using the scanline method overcomes the shortcomings of the original qualitative evaluation criteria. On the basis of the mine example, the unascertained measure theory is used in the evaluation and analysis of underground structural planes. The models of single- and comprehensive-index functions are constructed. Information entropy is used to determine the weight, whereas the confidence recognition criterion is used to evaluate the structural surface level.

(2) From the three middle section survey results of the mine, the unascertained measure theory is suitable to evaluate the structural plane. The evaluation results show that the structural evaluation grades of $R_1$, $R_2$, and $R_3$ are Grades III, IV, and IV, respectively. Therefore, middle sections $R_2$ and $R_3$ should establish a strengthened support to ensure safe operation. The unascertained measure theory provides a new method for structural plane evaluation by using the scanline method.

(3) As the geological structure surface is affected by many factors, further selecting accurate and reasonable underground structural surface parameters and grading standards in the future is necessary to ensure the reliability of the evaluation survey.

Data Availability

The test data used to support the findings of this study are included within the article. Readers can obtain data supporting the research results from the test data table in the paper.
Conflicts of Interest

No potential conflicts of interests were reported by the authors.

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