Risk assessment of high slope landslide in open-pit mine based on comprehensive geophysical prospecting

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Abstract. The landslide of high slope of open-pit ore rock poses a great threat to the safe production of open-pit mine and seriously affects the economic benefits of the mine. The risk of landslides for the mines where landslides have occurred should be assessed in order to avoid similar accidents. The mechanism of landslide in area C of Bayan Obo’s East mine was studied, and the comprehensive prospecting of seismic method, geological radar method and high-density electric method was carried out on all areas of the main east mine without landslide reinforcement. On the basis of comprehensive prospecting results, five indicators affecting slope stability, such as water content and fault combination mode, were selected. By making pairwise comparison between these five factors, the judgment matrix was constructed, and the weight matrix of each factor was obtained by transforming the judgment matrix. Based on experience and parameter sensitivity analysis, these indexes were divided into three levels: high risk, medium risk and low risk, and the degree of correlation between each factor and evaluation was calculated. Taking a section as an example, the gray fuzzy matrix and weight matrix were constructed, and the gray comprehensive fuzzy judgment was carried out to determine the landslide risk level of the section.

1. Introduction

The high slope landslide of open-pit mine causes not only the damage of equipment and casualties, but also a great loss of ore due to landslide, further resulting in the inaccurate definition of the lower boundary. Taking Bayan Obo’s East mine as an example, the loss of pressure ore caused by landslides amounts to hundreds of millions of yuan, and the annual cost of slope treatment reaches tens of millions of yuan. Therefore, it is of great significance to carry out geological exploration and landslide risk assessment in areas without landslide reinforcement, and to prevent landslide by means of reinforcement on this basis.

Traditional exploration is mainly geological survey and drilling. The geological survey costs are generally low, but drilling is accurate and costly, with a large deviation in results caused by the small number of drilling. The comprehensive prospecting method based on seismic method and geological radar method has achieved a good balance between exploration cost and final result. Despite it is limited by some terrain in practice, it is an efficient method. On the basis of engineering geophysical prospecting, this study uses comprehensive geophysical prospecting method to evaluate the landslide hazard of area in Bayan Obo’s East mine without landslide reinforcement [1].
2. Basic situation of the study area

Bayan Obo ore deposit is the largest rare-earth element (REE) deposit, the second largest niobium (Nb) deposit in the world, and also a large iron (Fe) deposit in China. The Bayan Obo deposit is located in the southern Mongolian plateau, approximately 90 km south of the China and Mongolia border, at 109°58′E and 41°48′N, located in the northern margin of the North China Craton (NCC), and connected to the Central Asian Orogenic Belt, as shown in Figure 1. The Bayan Obo giant REE-Nb-Fe deposit, hosted in the massive dolomite, occurs in one of the syncline cores. In the northern part of the ore body, a complete sequence of Bayan Obo Group is exposed in the Kuangou anticline, which is developed on the Paleoproterozoic basement rocks and has obvious angular unconformity, as shown in Figure 2 [2].

![Geological sketch map of the Bayan Obo area, northern China. Modified after Yang et al.(2011a).](image1)

![Geological section of line A-B in Figure 1, showing location of ore bodies.](image2)

The low grade clastic sequences of the Bayan Obo Group represent the sedimentary unit of the inner deposition of the Bayan Obo marginal rift, and the Bayan Obo deposit is just located in the
Bayan Obo continental margin rift in the northern North China Craton. The mine consists of three main ore bodies: east ore body, main ore body and west ore body. The eastern part and the main orebodies are distributed between the ore-bearing dolomite and the potassium-rich slate boundary of Bayan Obo Group. The West Orebody mainly occurs in massive dolomite. Relative to the West Orebody, the East and Main orebodies occur as larger lenses, as shown in Figure 3 [2]. The East Orebody is located in the northeast of Bayan Obo mining area, has freight railway and sandy road, the surface is desert grassland, no cash crop cultivation [3].

Drought and little rain in this area, as can be known from multi-year statistics, the lowest atmospheric precipitation is 131.5mm (1965), the highest is 373.1mm (1958), the average annual precipitation is 231.6mm, evaporation is more than 10 times larger than precipitation, rainfall is concentrated in July-August, accounting for more than half of the annual precipitation. The C area of East Mine in Bayan Obo iron mine is located in the northeast end of the East Mine stope. The slope is curved, and the overall slope is about 43 to 39 degrees, which gradually slows down from west to east. At present, a small part of the cut-off drainage failure, the surface has water through. The location of Area C is shown in Figure 4. The severe landslide hazard area and fault location are shown in Figure 5.

Figure 3. Geological map of the Main and East orebodies at Bayan Obo. Modified after Institute of Geochemistry, Chinese Academy of Sciences (1988).

3. Comprehensive geophysical prospecting method

Due to limited blasting technology, a four-horizontal parallel stage slope with an approximate height of 56 m was formed in the main east mine of Bayan Obo iron ore mine during production. Due to large angle, the slope was exposed to long-term weathering and affected by blasting vibration, resulting in surface cracks and even gravel slip. Therefore, in order to ensure the safety of researchers, it is not appropriate to use transient electromagnetic and other area-based slope exploration, nor is it suitable for geological radar hanging slope exploration. Based on the comprehensive consideration of mine topography and practical engineering needs, the seismic method, geological radar method and high-density resistivity method are used in this study [4, 5]. The layout of the west platform survey line is shown in Figure 4.
3.1. **Seismic method**

Seismic exploration is a geophysical exploration method based on the theory of elastic wave field based on the elastic physical properties of rocks. The research principle is to use artificial sources to excite seismic waves, when seismic waves travel to the ground encountered an elastic interface will be reflected and refracted, while the seismic exploration instruments laid in different locations along the line to detect the earth's subtle vibration. As seismic waves travel through the medium, their path, vibration intensity, and waveform will vary depending on the elastic properties and geometric form of the medium through which they pass. By processing and interpreting the recorded seismic waves, the nature and shape of the underground rock formations can be inferred effectively [6].

Due to the presence of large-scale mining equipment such as tooth turbine drilling rigs, electric shovels, electric wheels, crushing stations and belt conveyor in the main east mine and production
needs, high-voltage wires are distributed in the pit, leading to serious noise interference. In order to facilitate data collection and post-data processing, it is necessary to investigate the characteristics of interference sources and background noise in advance. This study investigates and analyzes noise interference source using MMS-1 multi-wave multi-component seismometer developed by China University of mining and Technology (Beijing). The frequency of background noise in the research area is less than 50 Hz, and the nearby noise cancellation distance is between 60 and 250 Hz, where the direct wave and reflected wave energy are strongly reflected. The far offset distance energy is weak, and low-frequency regular interference is strong, with a frequency of being generally between 10 and 50 Hz.

Shallow seismic exploration is carried out using the DZQ 48 high-resolution seismometer developed by Chongqing Geological Instrument Factory. A total of 48 channels are received with a distance of 2 m and a minimum offset of 2 m. Unilateral excitation occurs, covering 12 times. The excitation mode is 30 pound hammer, using 20 cm × 30 cm × 2 cm steel plate as pad. Due to the influence of interference waves and background noise, data processing and data interpretation show that the quality of data within 20 m is poor, and that the exploration results are favorable, being below 20 m. By comparing the original geological data, 32 new geological layers are discovered and 23 are verified, 6 of which are not detected due to interference and method limitations. Figure 6 is the seismic interpretation map of seismic line 6-6’. The survey line 6-6’ preliminarily explained 11 faults: F33 ~ F43, except F37, the occurrence is basically the same, and the fault dip angle is about 60 degrees. The broken band indicated by the dotted line corresponds to the landslide hazard area at high-density electrical sections 11.

![Seismic survey line 6-6’](image)

**Figure 6.** 1544 West platform 6-6’ seismic interpretation profile.

### 3.2. Geophysical radar method

The geological radar, also known as GPR, detects underground objects through electromagnetic waves in the process of its operation. The principle of the entire geological radar operation is as follows [7]: According to the propagation characteristics of electromagnetic waves in the consumed medium, the transmitting antenna emits high-frequency pulsed electromagnetic waves to the medium under test, and when it encounters an uneven body (interface), it reflects a part of the electromagnetic waves, the reflection coefficient mainly depends on the dielectric constant of the medium under test, and the radar host receives and processes the reflected waves in this part in a timely manner to achieve the purpose of detecting and identifying the target object. As shown in Figure 7.
The ZTR12 mine intrinsically safe geological radar system developed by China University of Mining and Technology (Beijing) is used for detection along the survey line. Prior to the detection, the measurement time window and sampling point experiments are carried out. The experimental results indicate that the geological radar image obtained is the optimal at 2,048 sampling points, 100 ms and 300 ms sampling time windows. Therefore, combined with these two parameters, the investigation is carried out respectively. It is found that the depth of the probe filling is 5 m through the bedrock, effectively detecting the distribution of rock fragmentation and weathering. Fracture zones are found on all survey lines, and the extension range of fracture zone accounts for about 25% of the total length. And the fracture zone of Platform 1544 is more serious than that of Platform 1488, with more fracture zones. The rockfall of cleaning platform is relatively serious. The Geological radar interpretation map corresponding to section 11 of high density resistivity method is shown in Figure 8. The waveforms of the marked areas in the figure are more cluttered, generally characterized by the corresponding features of cracks or faults, and interpreted as fissures. The section circled in the figure shows a large area of fissure, indicating the existence of obvious fracture zone. As the rainfall in the mining area is mainly concentrated in July and August, the areas circled in the figure may also develop into karst caves.

**Figure 7.** Schematic diagram of geological radar.

**Figure 8.** Geological radar interpretation map corresponding to section 11 of high density resistivity method.
3.3. High density resistivity method

High-density resistivity method is an electrical exploration method based on the electrical difference of rock and soil. According to the distribution law of formation conductive current under the action of electric field, the resistivity distribution in the formation is obtained, and the occurrence of geological bodies with different resistivity underground is inferred [8].

Since the exploration area is curved and the high-density resistivity method requires the line to be as straight as possible, some sections meeting the requirements of high-density electrometry are divided in practical exploration under the premise of allowing field topography and safety. The DUK-2B high-density electrical instrument developed by Chongqing Geological Instrument Factory is used for exploration, and 60 high-density electrical explorations with electrode distance of 4 m are carried out in the upper part of the slide in Area C. The spacing between each measuring line is 2 m. The maximum bathymetrics are 76 m and 38 m, respectively. After data inversion and denoising, it is found that there are obvious high-density electrometer line appearance characteristics of "two verticals and one horizontal" in four areas of the landslide. The elevation difference between the two places corresponds to the geographical coordinates, which has a high risk of bedding rock landslide. Figure 9 is a high-density resistivity profile at Section 11. According to the principle of electrical prospecting and the distribution characteristics of underground artificial electric field, when the sedimentary distribution of strata is uniform and not subject to any damage and change, the apparent resistivity changes evenly. If there are many factors such as fractures, rock water and faults, the apparent resistivity value is relatively smaller than that of the strata with uniform deposition distribution. There are two obvious low-resistivity banded anomaly zones in the figure. The interpretation conclusion is that the low-resistivity anomaly zone is a fault fracture zone, and the two fault zones tend to be opposite. There is a horizontal low-resistivity anomaly zone between the two fault zones, which is interpreted as a landslide hazard zone.

![Figure 9. High density resistivity profile at Section 11.](image)

4. Landslide mechanism of slide in Area C

From the landslide in 2000 to the slope-cutting treatment in 2006, there have been four landslides in Area C from 1 to 4. Through the field exploration and analysis of landslide, it is found that No. 1 and No. 2 landslide belongs to the category of bedding rock landslide. The boundary of No. 1 sliding mass is clear, the boundary isolation faults are F111 and F107, and the sliding surface is F91. The No.2 sliding mass has the characteristics of Grade 2 slip surface, and the boundary of the sliding mass is fault F16 and lamprophyre vein on the other side. According to the high-density electrical measurement line in the upper part of area C, the residual perimeter of No. 1 sliding mass and other characteristics cannot be detected.
Slides No. 3 and 4 are broken rock landslides, where rock breakage zone is developed, with a width of up to 15 m. Under the comprehensive influence of the upper slide block pushing, platoon action, blasting vibration and other factors, continuous collapse deformation occurs, resulting in landslides [9].

5. Slope stability assessment

Fuzzy comprehensive evaluation is based on fuzzy mathematics, applying the principle of fuzzy relationship synthesis, quantifying some factors with unclear boundaries and not easy to quantify, and starting with a number of factors to evaluate the status of the subordinate hierarchy of things. Based on the gray theory, the gray correlation evaluation calculates the correlation between each scheme and the optimal scheme, and compares and sorts the evaluation object according to the size of the correlation degree [10-12].

The size of slope risk and its corresponding relationship with the influencing factors belong to the fuzzy theoretical category, while the reliability of the results belongs to the gray theory category because of the multi-solution of prospecting. Therefore, the risk of slope landslide is assessed using gray fuzzy comprehensive evaluation [13-17].

5.1. Determination of factor set (U) and comment set (V)

The landslide modes of rock slope are bedding rock landslide and broken rock landslide because the evaluated area is rock slope. By examining the influence factors of these two landslides, the evaluation factors are selected as follows: "two verticals and one horizontal" fault combination model, water-bearing, the degree of tectonic development of deep rock bodies, surface rock crack development and fragmentation band distribution, and stage slope. The risk factors set is determined as:

\[ U = \{ u_1, u_2, u_3, u_4, u_5 \} \]

The risk of landslide instability is divided into small, medium and large levels. The corresponding set of comments is expressed as:

\[ V = \{ v_1, v_2, v_3 \} \]

A comprehensive study of the five factors, except for the stage slope and crack and fracture distribution, the rest can not be well quantified. The sensitivity of the influencing factors of slope stability is analyzed on the two indicators that can be quantified, and the criteria of small, medium and large risks are given in the analysis results. The remaining three quantities, which cannot be accurately quantified, are graded according to experience. The obtained grading indexes are shown in Table 1.

**Table 1. Stability classification of evaluation index.**

| Evaluation factors | Stage slope gradient \((u_1)(\degree)\) | The "two verticals and one horizontal" fault combination mode \((u_2)\) | Aquosity \((u_3)\) | Crack and break band distribution \((u_4)\) | Deep structural development \((u_5)\) |
|--------------------|----------------------------------------|-------------------------------------------------|-----------------|---------------------------------|-----------------|
| less risk \((v_1)\) | <80 | nil | nil | below 5% | Not developed |
| Medium risk \((v_2)\) | 80 ~ 88 | has, not typical | Sporadic distribution | 5% ~ 30% | Sporadic distribution |
| high risk \((v_3)\) | >88 | typical | More, concentrated distribution | The proportion is greater than 30% | more |
5.2. Determination of single-factor gray blur matrix
There are five factors and three comments in this review, so the single-factor gray blur matrix is expressed as:

\[
R = \begin{bmatrix}
(\mu_{11}, v_{11}) & (\mu_{12}, v_{12}) & (\mu_{13}, v_{13}) \\
(\mu_{21}, v_{21}) & (\mu_{22}, v_{22}) & (\mu_{23}, v_{23}) \\
\vdots & \vdots & \vdots \\
(\mu_{51}, v_{51}) & (\mu_{52}, v_{52}) & (\mu_{53}, v_{53})
\end{bmatrix},
\]

(1)

where \( \mu_{mn} \) denotes the membership degree of the mth factor to the nth comment, also known as the module of the gray fuzzy matrix. \( v_{mn} \) represents the gray level of the mth factor to the nth comment, that is, unreliability, which reflects the reliability of the result or the adequacy of information collection caused by limited technical factors, also known as the gray part of the gray fuzzy matrix. In this analysis, the adequacy of information collection is divided into five levels, namely: "very sufficient, more adequate, general, poor, very poor", with corresponding point grayscale of \{0 0.3 0.5 0.7 1\}.

The evaluation involves two indicators that become large factors and three qualitative factors. For indicators that become larger, there are:

\[
\mu_1(x) = \begin{cases}
1, & x \leq x_1 \\
\frac{x_2 - x}{x_2 - x_1}, & x_1 < x < x_2 \\
0, & x \geq x_2
\end{cases}
\]

\[
\mu_2(x) = \begin{cases}
1, & x \leq x_1, x \geq x_3 \\
\frac{x - x_1}{x_2 - x_1}, & x_1 < x < x_2 \\
\frac{x_3 - x}{x_3 - x_1}, & x_2 \leq x < x_3 \\
0, & x \leq x_2
\end{cases}
\]

\[
\mu_3(x) = \begin{cases}
0, & x \leq x_2 \\
\frac{x - x_2}{x_3 - x_2}, & x_2 < x < x_3 \\
0, & x \geq x_3
\end{cases}
\]

For qualitative evaluation factors, the degree of membership is 1; otherwise it is 0.

The 118 m region corresponding to the high-density electrical section 11 generates a single-factor gray fuzzy matrix based on geological data obtained by geological radar, high-density resistivity method and seismic method, as compared with the stage slope data obtained by the field measurement:

\[
R = \begin{bmatrix}
(0,0) & (3/8,0) & (5/8,0) \\
(0,0.5) & (0,0.3) & (1,0) \\
(0,0.5) & (1,0.3) & (0,0.7) \\
(0,0.3) & (0,2,0) & (0,8,0,3) \\
(0,1) & (0,0.5) & (1,0,3)
\end{bmatrix}.
\]

(2)

5.3. Determination of the weight matrix for each factor
First, the degree of importance between the factors of the judgment matrix is determined. The five factors of the judgment matrix used for assessment are shown in Table 2.
Table 2. Judgment matrix on importance of each factor.

| Level 1 factor | $u_1$ | $u_2$ | $u_3$ | $u_4$ | $u_5$ |
|----------------|-------|-------|-------|-------|-------|
| $u_1$          | 1     | 1/3   | 1/2   | 1/3   | 1     |
| $u_2$          | 3     | 1     | 2     | 1     | 2     |
| $u_3$          | 2     | 1/2   | 1     | 1/2   | 2     |
| $u_4$          | 3     | 1     | 2     | 1     | 3     |
| $u_5$          | 1     | 1/2   | 1/2   | 1/3   | 1     |

The characteristic vector of the matrix is calculated by root method, and the weight matrix containing the factors of slope instability with grayscale is synthesized:

$$A = \begin{bmatrix} (0.100, 2.0), (0.293, 8.0), (0.178, 7.0), (0.318, 6.0), (0.108, 7.0) \end{bmatrix}.$$ (3)

The maximum feature root of the comparison matrix is calculated as: $\lambda_{\text{max}} = 5.042 \, \text{5}$, insert formula

$$CR = \frac{CI}{RI} = \frac{\lambda_{\text{max}} - n}{RI(n-1)},$$

where $n = 5$. By checking the table to get $RI = 1.12$ and calculating the available $CR = 0.009 \, 5 < 0.1$, the weight matrix calculated above has satisfactory consistency and can be used for gray fuzzy judgment.

5.4. Comprehensive evaluation of gray fuzzy

The synthesis of the comprehensive evaluation factors is a weighted average model for the model, a mean model for the gray part, and a gray fuzzy matrix after the synthesis

$$B = A \cdot R = [(0.46, 0.28, 0.22), (0.72, 0.26)].$$ (4)

The corresponding paradigm is calculated as:

$$\|x_1\|, \|x_2\|, \|x_3\| = \{0.54, 0.828, 7.1032 \, 5\}$$ (5)

From the foregoing “The risk of landslide instability is divided into small, medium and large levels. The corresponding set of comments is expressed as: $V = \{v_1, v_2, v_3\}$ ”, the largest number is the third, that is, 1.032 5. Select the comment with the largest membership degree as the comprehensive evaluation result, so the evaluation result is “large”.

Therefore, according to the evaluation rules, the risk of instability in this section is large. According to the same rules, the risk of other sections of the Bayan Obo’s East mine can be assessed. The final result is shown in the blue box in Figure 4, which is the landslide severe hazard area.

6. Conclusions

Through comprehensive geophysical prospecting and grey fuzzy comprehensive evaluation, the slope stability of Bayan Obo’s East mine was analyzed, and the following conclusions were obtained:

1. The geological radar method, seismic method and high-density resistivity method were used for comprehensive prospecting on the horizontal steps of Bayan Obo’s East mine 1544 and 1488, and by optimizing the measurement parameters and improving the data processing process, the geological data reflecting the parameters of groundwater, broken zone, fault combination structure were obtained. It provides the basis for the management of mine slope.

2. The angle of stage slope, water content and other parameters were selected, and the gray fuzzy comprehensive evaluation method was adopted. Taking high-density electricity section 11 as an example, the area was judged to be unstable.
(3) Providing a feasible method for slope instability evaluation by combining comprehensive prospecting with gray comprehensive fuzzy evaluation.

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