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# Stability Analysis and Optimization Design of Composite Slopes in Open-Pit Mines

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**Abstract:** ***Mineral resources play a crucial role in modern construction, and open-pit mining is the primary method for resource extraction. Ensuring slope stability is vital for the normal operation of open-pit mining. This study focuses on an open-pit coal mine in Xilin Gol League, Inner Mongolia, China. Through comprehensive methods such as geological data collection and analysis, field investigation, and UAV mapping, the Slope/W module in GeoStudio software was employed, and the Bishop limit equilibrium method was used to perform a stability analysis on two cross-sections of the composite slope between the mining pit's East Slope and the external dumping site. The results showed that the safety factors for these two sections of the composite slope do not meet the required reserve safety factor. After applying a toe-weighting optimization design, a subsequent stability analysis was conducted, ensuring the stability requirements were met. The main factors affecting the stability of the composite slope were analyzed, including the geotechnical properties, slope rock mass structure, the design distance between the external dumping site and the mining slope, and surface water erosion and seepage. Safety and mitigation recommendations were proposed for other open-pit mines with composite slopes involving external dumping sites and mining slopes.***

**Keywords:** Open-pit mine, Composite slope, Stability analysis, Bishop**.**

## 1. Introduction

Mineral resources play a critical role in modern infrastructure development, providing a solid foundation for the production and daily life of the population. Open-pit mining is the primary method for extracting mineral resources, and with the continuous increase in extraction depth, the height of open-pit slopes has also grown [1], leading to a higher risk of slope instability, which can result in geological hazards [2][3]. Ensuring slope stability is essential for the safe operation of open-pit mining, protecting the lives and property of mine workers [4][5].

During open-pit mining, in order to optimize waste disposal operations, reduce the transportation distance of discarded material, lower transportation costs, and maximize the use of limited external dumping space, the external dumping site is typically located near the mining area. This results in the formation of a composite slope between the mining pit and the external dumping site. The failure mechanism of composite slopes is more complex, as the mining slope is subjected not only to its own gravitational load but also to additional loads from the external waste disposal [6][7], generating additional stresses within the rock mass [8][9][10][11]. Once a composite slope fails, the damage is often more severe. Therefore, the stability analysis and optimization design of the mining pit-external waste disposal composite slope are crucial for ensuring the safe production and sustainable development of open-pit mines.

With the continuous advancement of technology, slope stability analysis methods and techniques have significantly improved, providing more scientific and reliable support for mining safety. López-Vinielles, J et al. [12] proposed a method for geological modeling through digital photogrammetry and satellite radar interferometry, enabling remote analysis of open-pit slope stability. Wang, W et al. [13] performed finite element analysis of slope stability, gaining deeper insights into the effects of weak layers on slope instability. C. Romer [14] studied the influence of structural faces on the stability of open-pit rock slopes. Zeng et al. [15] conducted slope stability analysis using the Bishop method for open-pit slopes. Gao et al. [16] utilized 3D laser scanning to study the stability of steep slopes. Liang Z et al. [17] proposed a 3D stability calculation method for large composite slopes formed by adjacent open-pit mining areas and internal waste disposal sites. Jiang J et al. [18] introduced a slope stability evaluation method based on Poset theory. Li Z et al. [19] integrated 3D numerical modeling and data monitoring for stability analysis of open-pit slopes.

This paper focuses on an open-pit coal mine in Xilin Gol League, Inner Mongolia, China. By collecting and analyzing geological data, conducting field surveys, and using UAV mapping, the stability analysis and optimization design of the composite slope between the East Slope of the mining pit and the external waste disposal site were carried out. Additionally, the influencing factors of composite slope stability were explored. Based on the analysis results, preventive and control measures for the instability and failure of the composite slope were proposed, along with recommendations, offering a reference for similar research.

## 2. Geological Settings

The study area is located in Xilingol League, Inner Mongolia, China, with geographic coordinates ranging from 117°00′46″E to 117°03′26″E and from 45°15′22″N to 45°17′15″N. The mining area is situated in the central part of the Inner Mongolia Plateau, which is characterized by low mountainous terrain and hills. The topography exhibits a north-south gradient, with the highest elevation in the northwest reaching 1143.9 meters and the lowest point in the south at 847.7 meters. The vertical distance between these points varies from several dozen meters to over one hundred meters, creating relatively moderate topographic variations. Overall, the terrain is relatively flat, with gentle slopes and undulating landforms that provide a stable base for mining operations.

The primary geological units in the study area include the Lower Cretaceous Bayanhu Formation (K1b), the Upper Miocene (N2) of the Tertiary period, and the Quaternary (Q4). The lithology is predominantly composed of sandstone, mudstone, and clay, which are common in this region. These sedimentary rock types contribute to the geological characteristics that influence slope stability in the area.

Fault structures in the study area are mainly developed in the Lower Permian and Upper Carboniferous strata. The faults are primarily small-scale, step-like, and arranged in an en echelon pattern. These faults generally trend in an east-west direction or northeast-southwest direction, reflecting the regional tectonic stress regime. The fault displacements are relatively small, with normal faults typically dipping northwest at angles between 47° and 57°, while reverse faults dip to the north or northwest at angles less than 30°. These structural features can influence the stability of the slopes, especially when interacting with the mining activities. Importantly, no active faults have been identified within the open-pit mining area itself, indicating a relatively low seismic risk in this specific region. However, the local fault structures may still have indirect effects on slope behavior and require careful consideration in the stability analysis and optimization of the mining pit slopes.This expanded version provides more context and details about the terrain, geological formations, and fault structures, which are crucial for understanding the area's geological conditions in the context of slope stability.

The study area is located in the temperate continental climate zone, characterized by high altitude and situated in the inland region of the mid- and high-latitude zone, where the natural conditions are relatively harsh. The climate is influenced by the Mongolian high-pressure system in winter, bringing cold temperatures and strong winds, while summer is marked by concurrent heat and precipitation. The average annual temperature is 1.6°C, with an average temperature of -18.9°C in January and 21°C in July. The extreme maximum temperature recorded is 39.7°C, while the minimum temperature can reach as low as -40.7°C. The growing season (with daily temperatures above 5°C) lasts for about 95 days, and the frost-free period averages 120 days. The annual precipitation is approximately 300mm, with the majority falling between June and August, accounting for about 70% of the total annual precipitation. A location map of the study area is shown in Figure 1.

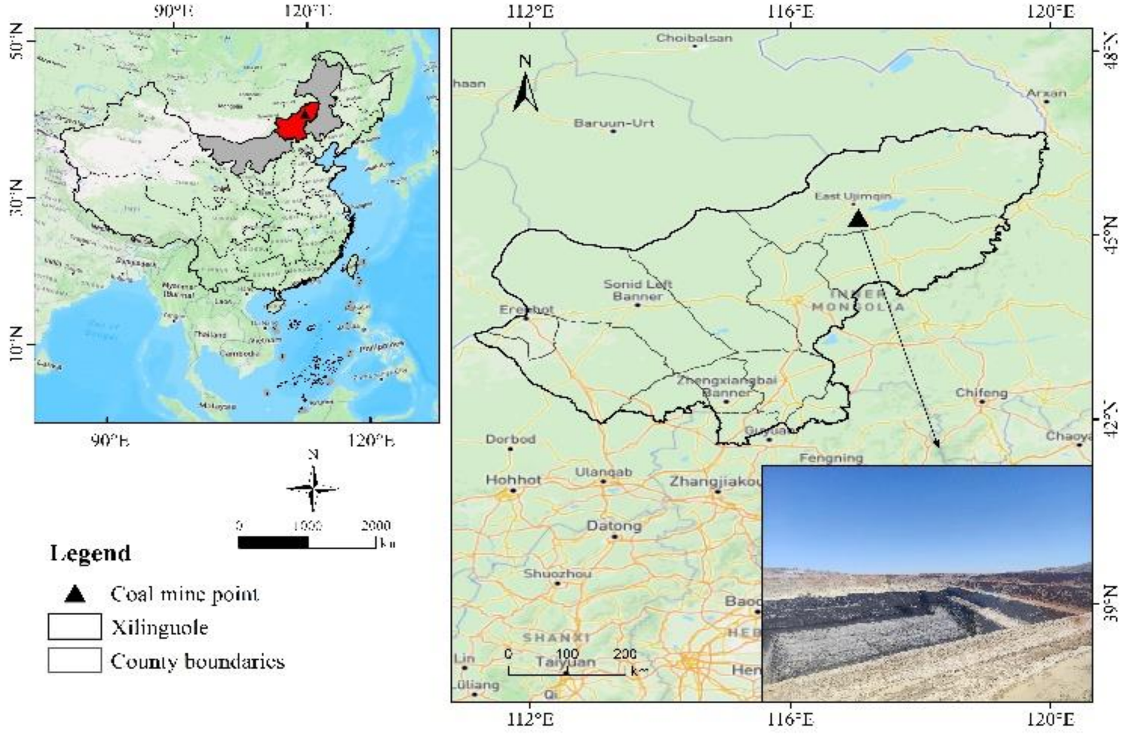

**Figure 1:** Geographical location map of the research area

## 3. Methods

### 3.1 Principle of Stability Analysis

In this study, the Slope/W module in GeoStudio software was used to perform stability calculations for the slope. The Bishop limit equilibrium method was employed to analyze the stability of the non-composite slope in the open-pit mine (as shown in Figure 2). The sliding surface is a circular arc with a radius of R and a center at O. The sliding mass is divided into n vertical slices. The i-th slice has a height of hi, a width of bi, a base sliding surface length of li, and an inclination angle of αi. Qi represents the seismic force (either blasting-induced seismic force or earthquake force). Ni and Ti represent the total normal and shear forces at the base sliding surface, respectively. Ei and Xi denote the normal and shear inter-slice forces, and ei is the perpendicular distance from the seismic force application point to the center of the circle. Wi is the gravitational force acting on the slice. This method assumes that the (n-1) X forces are zero (X=0), and the action points of the n normal forces are considered. Based on this assumption, the formula for calculating the safety factor can be derived:

$$F_s = \frac{\sum_{i=1}^{n}[C_i * b_i + (W_i - u_i * b_i) * \tan\varphi_i]/m\alpha_i}{\sum_{i=1}^{n} W_i * \sin\alpha_i + \sum_{i=1}^{n} Q * \frac{e_i}{R}} \tag{1}$$

$$m\alpha_i = \cos\alpha_i + \sin\alpha_i * \tan\alpha_i / F_s \tag{2}$$

In the equation, Ci and φi represent the cohesion and friction angle of the base of the slice, respectively; ui is the pore water pressure at the bottom of the slice.

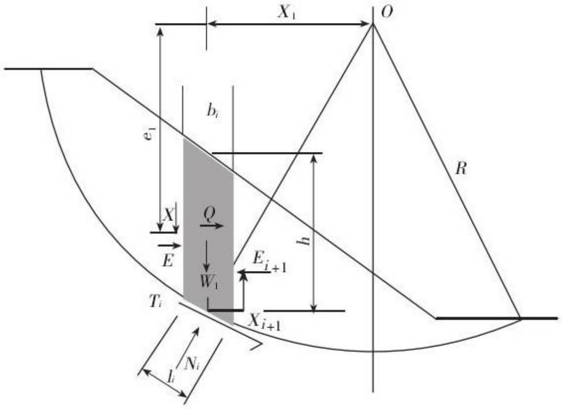

**Figure 2:** Blocking force of Bishop method

### 3.2 Profile Selection and Parameter Identification

Aerial photogrammetry using drones was conducted for the mining area, and modeling was completed to obtain remote sensing imagery and elevation data. Based on this, two profiles of the East Slope of the mining area and the external spoil dumping site composite slope were selected for stability analysis, as shown in Figure 3. Considering that the East Slope of the mining area is influenced by the load from the upper spoil dumping site, with a service life of less than 20 years, and the slope is relatively prone to instability due to its dip direction, the safety factor is determined to be 1.2, in accordance with relevant industry standards. Based on the borehole tests conducted by the mining company, and the empirical reduction of the physical and mechanical properties of the various strata, combined with the regional engineering geological conditions, the physical and mechanical properties of the rock mass were determined, as shown in Table 1.

**Table 1:** Geotechnical Physical and Mechanical Properties

| | Unit weight (Kn/m$^3$) | Angle of internal friction (°) | Cohesion (kPa) |
|---|---|---|---|
| Clay | 18.13 | 21 | 45.13 |
| Sandstone | 24.32 | 29 | 760 |
| A2 Coal | 11.858 | 30.5 | 350 |
| Siltstone | 25.28 | 25 | 980 |
| A1 Coal | 11.86 | 30.5 | 350 |
| Mudstone | 26.32 | 30 | 880 |
| Discarded soil | 18.50 | 25.1 | 46 |

**Figure 3:** Selection of Slope Profile Location

## 4. Results

### 4.1 Stability Analysis Results of the Composite Slope

A geological model was established based on the slope profile FH01. First, the geological data provided by the mining company and the drone survey data were integrated to accurately construct the profile geological model. Based on this, a detailed stratigraphic division was conducted to ensure the accurate representation of each geological unit. The water table was set based on field investigation and hydrogeological data. The detailed analysis is shown in Figures 4 and 5. The calculated factor of safety is 1.047, which is lower than the required safety reserve factor of 1.2, indicating that it does not meet the safety reserve factor requirement.

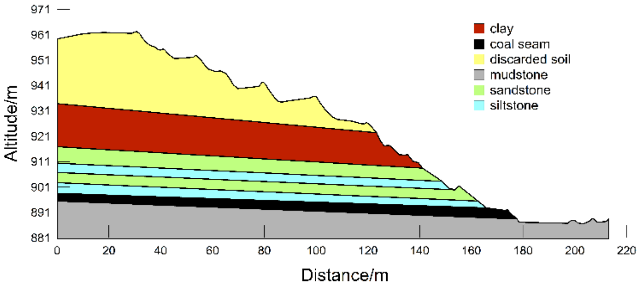

**Figure 4:** Composite Slope FH01 Profile Geological Model

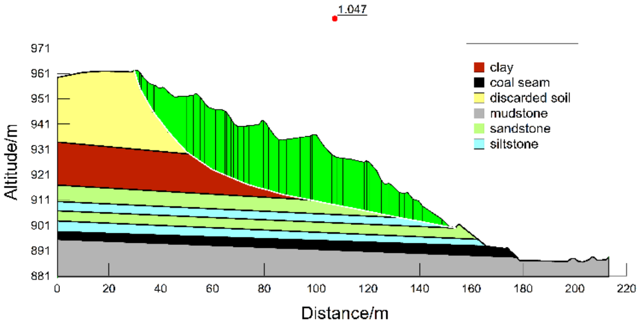

**Figure 5:** Stability Analysis Results of FH01 Profile

A geological model was established based on slope profile FH02. Initially, the geological data provided by the mining company and the drone survey data were integrated to accurately construct the profile geological model. Based on this, a detailed stratigraphic division was carried out to ensure the accurate representation of each geological unit. The groundwater table was set according to field investigations and hydrogeological data. The specific analysis is shown in Figures 6 and 7. The calculated safety factor is 1.089, which is lower than the required safety reserve factor of 1.2, indicating that it does not meet the safety reserve factor requirement.

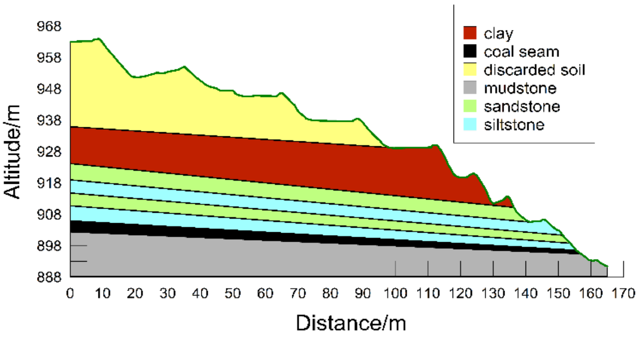

**Figure 6:** Composite Slope FH02 Profile Geological Model

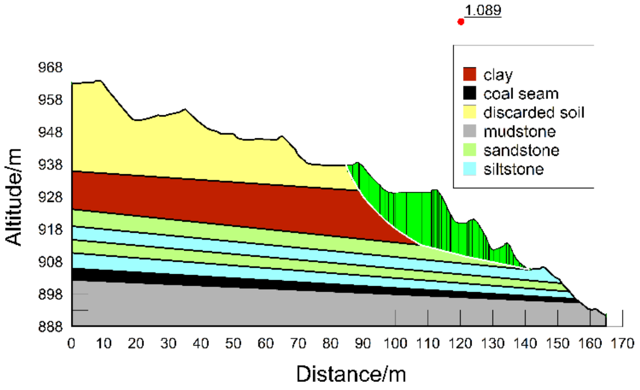

**Figure 7:** Stability Analysis Results of FH02 Profile

### 4.2 Optimized Design

Based on the calculated stability factors for the slopes mentioned above, it is clear that the stability factors of the composite slopes at the East Slope of the Mining Area and the External Dumping Site (FH01 profile and FH02 profile) are lower than the required safety reserve factor of 1.20. Therefore, an optimization design is carried out to ensure that the safety factor of the slopes meets the required safety reserve factor, ensuring safe production. The optimization design of open-pit mine slopes generally includes two main measures: slope reduction and toe reinforcement. These methods effectively improve the slope stability and reduce the risk of slope failure, thereby ensuring the safe operation of the mine. Below, the slope optimization design is presented based on the actual conditions of the mining area.

According to the actual conditions, toe reinforcement was applied to the composite slope of the East Slope of the Mining Area and the External Dumping Site (FH01 profile), reducing the overall slope angle from 26° to 20.39°. After recalculating using the limit equilibrium method, the safety factor was found to be 1.239, which is greater than the required safety reserve factor of 1.2, thus meeting the safety reserve factor requirement. The results are shown in Figures 8 and 9.

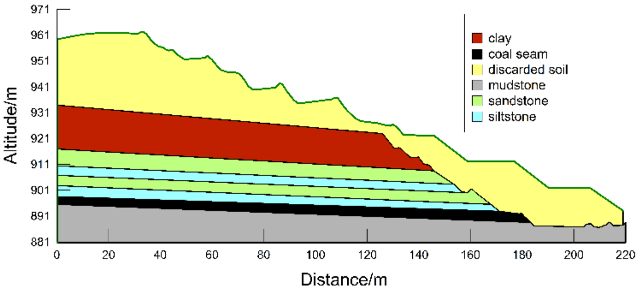

**Figure 8:** Optimized Design Model of FH01 Profile

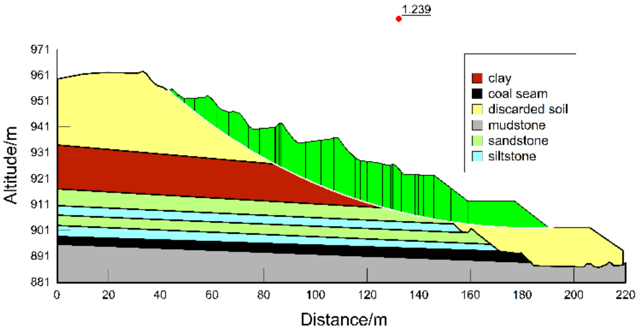

**Figure 9:** Stability Analysis Results of Optimized Design for FH01 Profile

Based on the actual conditions, toe reinforcement was applied to the composite slope of the East Slope of the Mining Area and the External Dumping Site (FH02 profile), reducing the overall slope angle from 26° to 18.35°. After recalculating using the limit equilibrium method, the safety factor was found to be 1.420, which is greater than the required safety reserve factor of 1.2, thus meeting the safety reserve factor requirement. The results are shown in Figures 10 and 11.

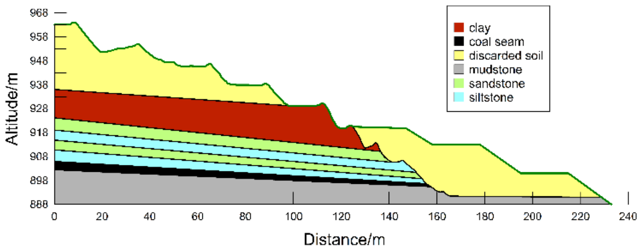

**Figure 10:** Optimized Design Model of FH02 Profile

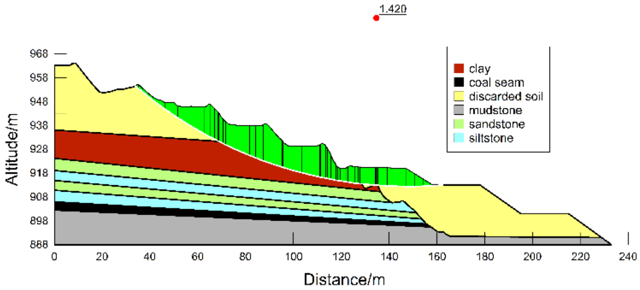

**Figure 11:** Stability Analysis Results of Optimized Design for FH01 Profile

## 5. Discussion

### 5.1 Verification of Stability Calculation Results

A detailed field investigation was conducted on the composite slope of the East Slope of the Mining Area and the External Dumping Site, revealing deformation traces. A north-south trending crack was visible in the upper part of the composite slope, extending for a linear distance of up to 200 meters. The crack is arcuate in shape (as shown in Figures 12 and 13), with extensions on both sides forming lower steps. The total estimated length of the crack is approximately 400 meters. A steep scarp is visible at the rear of the crack, with a dip direction of 91° and a dip angle of 80°. Vertical striations are observed on the crack surface, with a length of 85 cm. The most dangerous sliding surface in the stability analysis of the composite slope shows that the shear entry point is located on the external dumping site, which is consistent with the distribution of the rear crack observed during the field investigation.

**Figure 12:** Panoramic View of the Back Edge Fracture of the Composite Slope

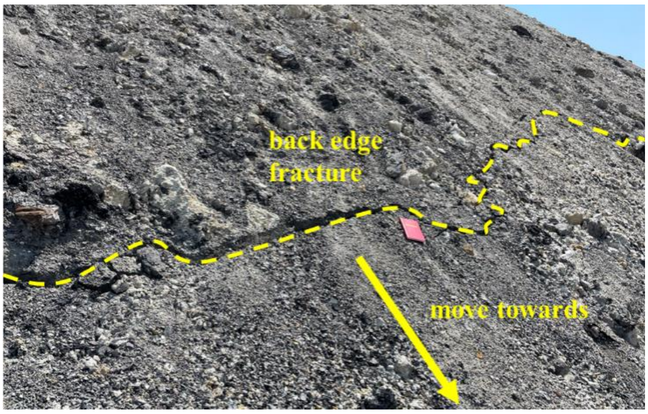

**Figure 13:** Close-up View of the Back Edge Fracture of the Composite Slope

At approximately 910 meters elevation on the composite slope of the East Slope of the mining area and the external waste dump, the original rock layers have undergone displacement along a weak plane, primarily consisting of sandstone. After excavation of the original rock, the slope layers are observed to displace outward from north to south, with the maximum displacement reaching 5-6 cm, as shown in Figure 13. The stability analysis of the composite slope indicates that the most critical sliding surface has its shear entry point between 900 and 930 meters elevation on the East Slope of the mining area, which aligns with the distribution of front-edge fractures observed during the field investigation.

**Figure 14:** Displacement at the Front Edge of the Composite Slope

A comprehensive analysis of the stability results for the East Slope of the mining area and the external waste dump composite slope profiles FH01 and FH02 shows that the most dangerous sliding surfaces identified through automated searching are consistent with the field survey results, and the calculation results are highly reliable. Since the stability factor of the composite slope did not meet the required safety reserve factor, the author performed an optimization design, considering both economic and safety factors. Ultimately, the toe-pressing measure was selected as the preventive measure. A stability analysis was then conducted on the optimized composite slope profiles to ensure that they meet the stability requirements and safeguard production safety.

### 5.2 The Analysis of Factors Affecting the Stability of Composite Slopes

Based on the stability analysis results of the composite slope at the East Slope and external waste dump of the open-pit mine, as well as the field investigation, the main influencing factors on the slope stability are comprehensively analyzed.

1) Geotechnical properties of the rock mass: The rock mass primarily consists of sandstone, mudstone, and clay, which are susceptible to weathering and have relatively poor physical and mechanical properties, leading to reduced strength and increased risk of instability.

2) Slope rock mass structure: The slope exhibits a dip in the direction of the excavation (dipping slope), which is more prone to instability compared to anti-dipping slopes, where the dip direction opposes the excavation.

3) Proximity between the external waste dump and the mining slope: The relatively short distance between the external waste dump and the mining slope results in additional load from the waste dump on the mining slope. This increases the induced stress within the rock mass, making the slope more vulnerable to instability compared to typical slopes.

4) Surface water erosion and seepage: The field survey revealed that each level of the composite slope is affected by surface water erosion and seepage, leading to the formation of collapse pits. The largest pit observed was approximately 2 meters in length and 30 centimeters in width (as shown in Figure 14). Some of the collapse pits exhibit a "string-of-pearls" pattern (as shown in Figure 15), which weakens the shear strength of the rock mass and soil, further compromising slope stability.

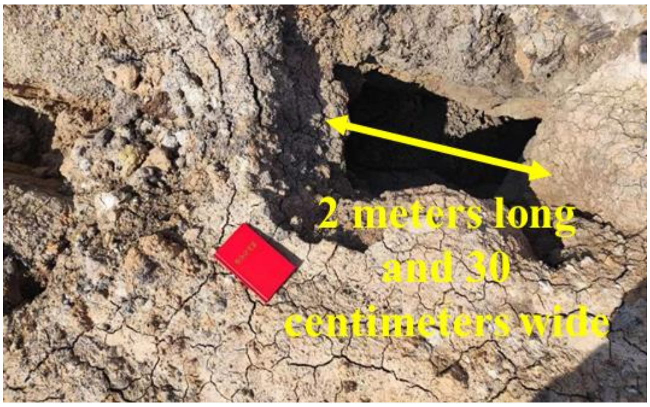

**Figure 15:** Collapse pits caused by surface water erosion and seepage

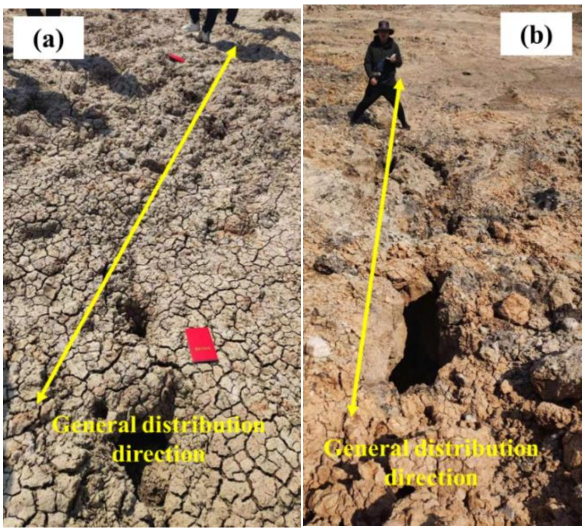

**Figure 16:** Bead-shaped distribution of collapse pits; (a) Strike: 341°; (b) Strike: 160°

## 6. Conclusion

This paper conducts a stability analysis and optimization design for the composite slope of the East Slope of the Mining

Area and the External Dumping Site at a coal mine in Xilin Gol League, Inner Mongolia, China. At the same time, the main factors influencing the slope stability are analyzed, and the following conclusions are drawn:

1) Two profiles of the composite slope of the East Slope of the Mining Area and the External Dumping Site were selected for modeling based on mining data and UAV survey results. The stability of the slope was analyzed, and the safety factors were found to be 1.047 and 1.089, which do not meet the required safety reserve factor of 1.2.

2) Optimization design was carried out for the two profiles of the composite slope that did not meet the safety reserve factor requirement, using toe-stretch measures for stabilization. The stability analysis was then conducted on the optimized slope profiles, resulting in safety factors of 1.239 and 1.420, which meet the stability requirements.

3) The main factors affecting the stability of the composite slope were found to be the geotechnical properties of the soil and rock mass, the structure of the slope rock mass, the design distance between the external dump and the mining slope, and surface water erosion and infiltration.

4) It is recommended that other open-pit mines with external dump–mining slope composite slopes pay attention to the distance between the external dump and the mining slope, implement effective water management measures, prevent surface water erosion and infiltration from damaging the slope, and promptly remove internal waste after coal layer extraction below the composite slope.

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