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Slope Stability Analysis of the Mining Pit in an Open-Pit Nonmetallic Mine

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Abstract: The scale of high and steep slopes formed in open-pit mining differs significantly from that in other engineering fields. Due to the extensive range of potential mining sites, the geological conditions of slopes often fail to meet ideal standards, making slope stability analysis critically important. This study examines the slope of an open-pit nonmetallic mine, discussing the primary influencing factors on slope stability, including external factors (stratigraphic lithology and slope geometry) and internal factors (groundwater, blasting vibrations, and natural climate). The finite element strength reduction method was employed to analyze and calculate slope stability, followed by evaluations and recommendations based on the computational results.

Keywords: Open-pit mine slope, Slope stability analysis, Finite element strength reduction method

1. Introduction

In recent years, with the rapid development of the national economy, industrial production has reached new heights. As the industry continues to standardize and improve, public awareness of safety has also increased, and national safety requirements have become more stringent. One of the most critical issues today is ensuring safe production in enterprises. Among these concerns, the stability of open-pit mine slopes has always been a key focus for mining companies, as research outcomes directly impact production safety, economic benefits, and social outcomes. Moreover, slope stability plays a vital role in the safe operation of open-pit mining activities and the protection of personnel and equipment. The long-term stability of the final pit slope determines the mining stability throughout the entire life cycle of the open-pit mine. Therefore, conducting research on slope stability is of utmost importance.

2. Project Overview

The open-pit nonmetallic mine is located in the Yinshan Uplift of the Inner Mongolian Platform within the North China Craton, where fold and fault structures are well-developed. The dominant tectonic feature is the Wulashan Anticlinorium, which extends in a topographic trend, with its axial zone situated in the Shetaichuan Valley between the Wulashan Mountains and Sertengshan Mountains. The mining area is located on the northern limb of this anticlinorium, where the exposed strata predominantly consist of south-dipping monoclinal structures.No major faults have been identified in the area. However, a few large-scale dikes may have intruded along fracture zones. Due to the substantial size of these intrusive bodies, no clear fault indicators remain.

The main exposed strata in the mining area include:Diorite,Amphibole-plagioclase gneiss,Migmatitic amphibole-plagioclase gneiss,Granitic pegmatite.

The observed intrusive rocks consist primarily of:,K-feldspar granite,Greisenized porphyritic K-feldspar granite,Quartz veins,Granite porphyry dikes.

Based on existing geological data, the rock mass within the final pit limits mainly comprises:Quaternary unconsolidated deposits,Moderately to highly weathered rock formations,Slightly to unweathered rock formations.

3. Factors Influencing Slope Stability

(1) Stratigraphic Lithology.Stratigraphic lithology refers to the characteristic properties of rocks, including color, texture, and composition. Generally, slopes composed of more competent rock exhibit better stability.

(2) Geometric Characteristics of Slopes. The geometric characteristics of a slope refer to its height, slope angle, surface morphology, and free-surface conditions. Slope stability is primarily influenced by its shape and scale, which induce tensile stress concentration in the crest region, leading to the formation of tension cracks. Additionally, shear stress is significantly enhanced at the toe of the slope, resulting in a shear failure zone. These effects markedly reduce the overall stability of the slope. Generally, for homogeneous slopes, steeper gradients and greater heights correspond to poorer stability. Therefore, the overall slope angle and morphology are also critical factors affecting slope stability.

(3) Groundwater.Groundwater is one of the most common factors affecting slope stability. Its impact on slope rocks is closely related to the rock structure of the mine slope, which can be specifically divided into two aspects:Physicochemical effects of groundwater: Through prolonged interaction with rocks, groundwater can alter the material composition, fabric, and even the structure of rocks.Mechanical effects of groundwater: Groundwater influences the stress state of slope rocks through mechanical actions. Typically, groundwater affects slope stability through the combined action of these two effects.

(4) Blasting Vibrations.In open-pit mining operations, blasting is typically employed to accelerate excavation progress, while inevitably affecting slope stability. The primary safety hazards induced by blasting vibrations stem from their loosening effects and dynamic actions.Mechanically analogous to seismic events, blasting vibrations can:Dilate structural discontinuities in slope rock masses,Induce rock fragmentation or loosening,Compromise the integrity of rock masses,Ultimately trigger slope instability.The dominant destabilizing mechanisms include:Shear effects: Reducing interlocking forces along discontinuities,Impact effects: Generating transient stress waves.These combined actions degrade key geomechanical parameters of slope rock masses, thereby impairing overall slope stability.

(5) Natural Climate Conditions.During winter, temperatures in the mining area are relatively low. When fissure water in the surface bedrock freezes, it exerts significant pressure on the fracture walls, causing them to expand outward. As temperatures rise and the ice melts, the pressure on the fracture walls decreases abruptly, allowing them to retract. Through repeated freeze-thaw cycles, rock fractures gradually widen and multiply, leading to the detachment of slope blocks and a continuous decline in the physical-mechanical strength of the slope rock mass. This process adversely affects local slope stability. Therefore, timely treatment of water seepage in the pit slopes is essential to fundamentally mitigate the impact of freeze-thaw cycles on slope stability.

4. Slope Stability Analysis and Calculation

According to the *Technical Code for Slope Engineering of Non-Coal Open-Pit Mines* (GB51016-2014), the hazard level of the slope is classified as Grade I based on the potential for casualties and direct economic losses in the event of slope failure. Depending on the final slope height of each section:For heights ranging 300 m < H < 500 m, the slope engineering safety level is Grade I.For heights ranging 100 m < H < 300 m, the slope engineering safety level is Grade II.As stipulated in Article 3.0.2 of GB51016-2014, slopes with heights between 300 m and 500 m are defined as high slopes. Furthermore, considering the potential hazards (casualties and economic losses), the minimum safety factor limits for Grade I slopes under different load combinations are as follows:

Load Combination I: Self-weight + groundwater, safety factor limit [K] = 1.25.

Load Combination II: Self-weight + groundwater + blasting vibration, safety factor limit [K] = 1.23.

Load Combination III: Self-weight + groundwater + seismic force, safety factor limit [K] = 1.20.

Per GB51016-2014, the stability assessment criteria are as follows:If the calculated safety factor K > [K], the slope is stable and has potential for a steeper angle. If 1 < K < [K], the slope is marginally stable.If K < 1, the slope is unstable, requiring slope angle reduction or engineering measures to enhance stability.

For the slope stability analysis of the mining area, five representative cross-sections were selected for 2D stability calculations based on field investigations and 3D numerical modeling results. These sections are designated as:N-N′, N1-N1′, E-E′, S-S′, and W-W′.

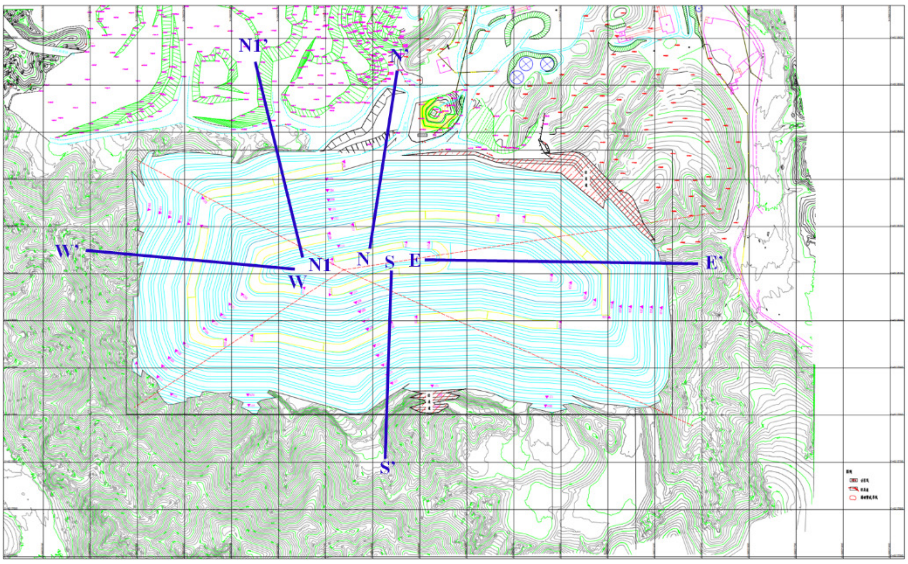

Figure 1. Layout Plan of Slope Engineering.

4.1 Finite Element Strength Reduction Method

The Finite Element Strength Reduction Method (FEM-SRM) is an integrated slope stability assessment system that combines the strength reduction theory, limit equilibrium principles, and elastoplastic finite element analysis. Its fundamental concept involves progressively reducing the shear strength parameters (cohesion *c* and internal friction angle φ) of the rock-soil mass until the model reaches a critical failure state. This allows for the determination of the failure mechanism and the corresponding safety factor.

When applied to mining areas with complex geological conditions, this method effectively accounts for the nonlinear elastoplastic behavior of the entire mining zone and fully considers the influence of deformation on stress distribution. Unlike conventional approaches, it eliminates the need for prior assumptions about the geometry of potential slip surfaces or discretization techniques such as the slice method (e.g., Bishop or Morgenstern-Price). Consequently, the analysis becomes more efficient and accurate in deriving the safety factor.

4.2 Slope Stability Analysis

(1) Stability Analysis of the Northern Mining Area Design Boundary (Section N-N′)

Based on the topographic map and geological survey, a two-dimensional section model was established. The strength reduction method was employed to determine the safety factor and potential slip surface of the unstable zone in the northern mining area. According to the calculation results, the safety factor of this section is 1.477. Referring to the requirements for a Grade I slope safety standard, the safety factor limit must exceed 1.20. Therefore, the overall stability of this section is favorable.

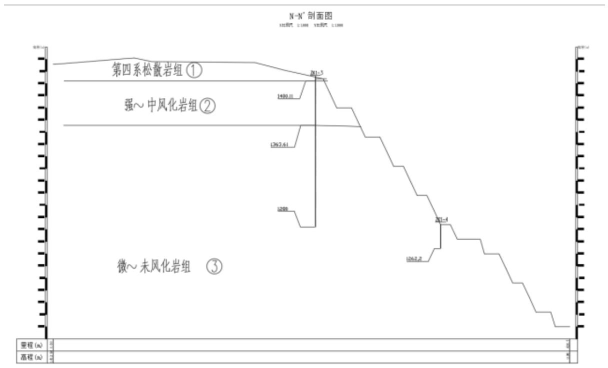

Figure 2. Stratigraphic Profile Diagram.

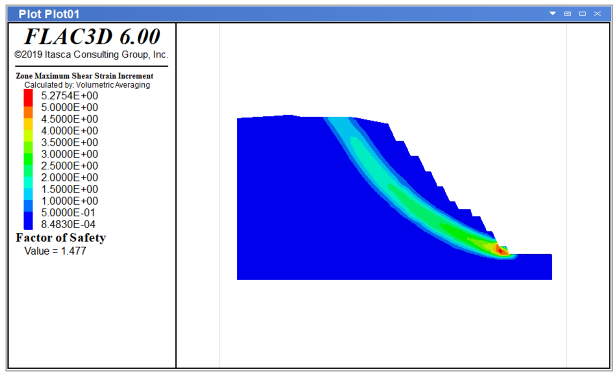

Figure 3. Safety Factor and Potential Slip Surface.

(2) Stability Analysis of the Northern Mining Area and Northwest External Waste Dump Design Boundary (Section N1-N1´)

According to the calculation results, the safety factor of this section is 1.430, indicating relatively good overall slope stability.

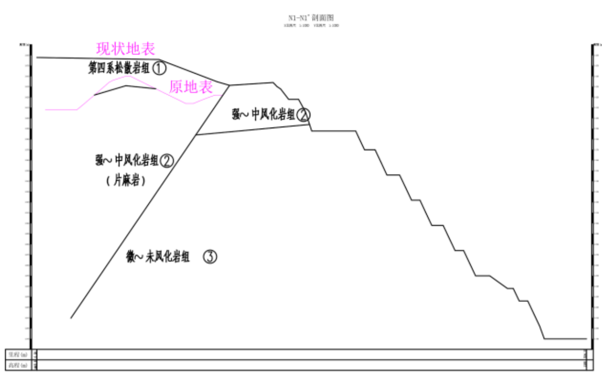

Figure 4. Stratigraphic Profile Diagram.

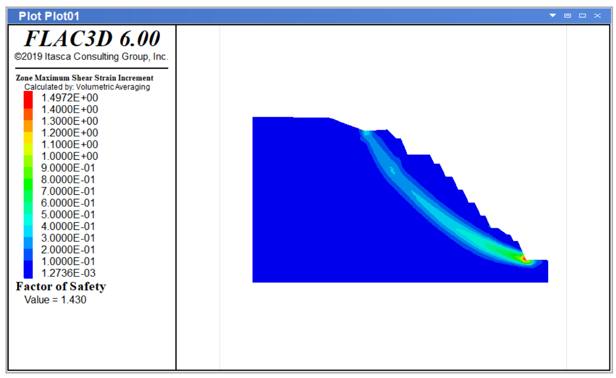

Figure 5. Safety Factor and Potential Slip Surface.

(3) Stability Analysis of the Eastern Mining Area Design Boundary (Section E-E´)

The calculation results show that this section has a safety factor of 1.684, indicating good overall slope stability.

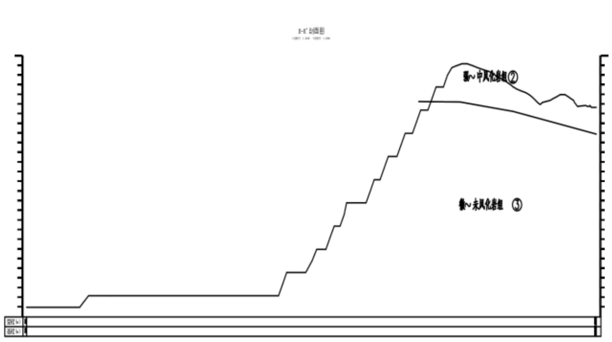

Figure 6. Stratigraphic Profile Diagram.

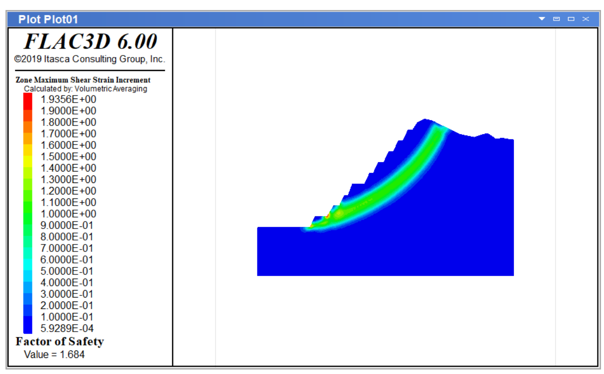

Figure 7. Safety Factor and Potential Slip Surface.

(4) Stability Analysis of the Southern Mining Area Design Boundary (Section S-S´)

The calculation results indicate that this section has a safety factor of 1.207, demonstrating relatively good overall slope stability.

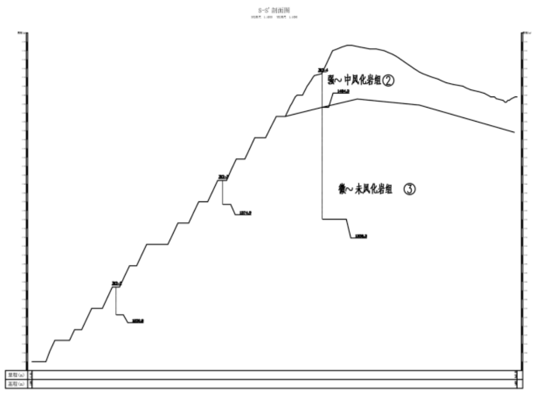

Figure 8. Stratigraphic Profile Diagram.

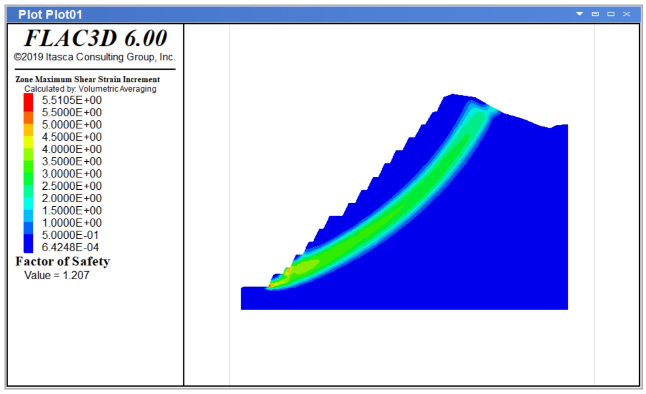

Figure 9. Safety Factor and Potential Slip Surface.

(5) Stability Analysis of the Western Mining Area Design Boundary (Section W-W′)

The calculation results show that this section has a safety factor of 1.320, indicating good overall slope stability.

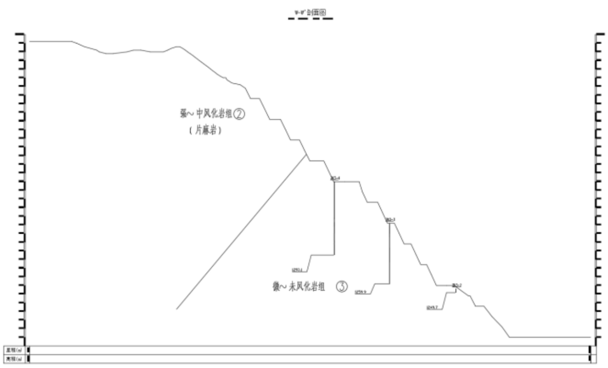

Figure 10. Stratigraphic Profile Diagram.

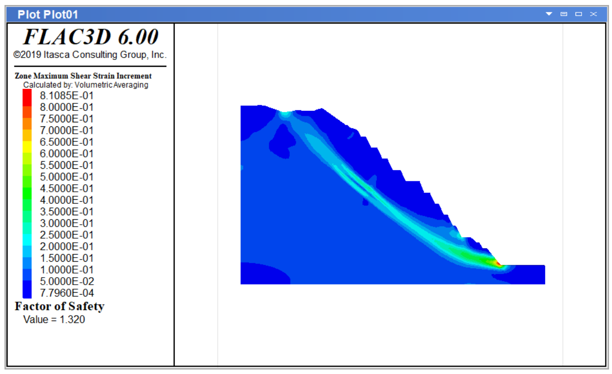

Figure 11. Safety Factor and Potential Slip Surface.

4.3 Calculation Results

Based on the aforementioned slope stability analysis and extensive field investigations and tests, it has been determined that the overall slope angle is a key parameter affecting both stability and the stripping ratio. The recommended values of the overall slope angle and their corresponding safety factors for the five sections are presented in **Table 1**.

Table 1. Recommended Overall Slope Angles Calculated by Bishop Method.

Section Number	Overall slope angle of design boundary	Recommended slope angle variation	Optimized recommended angle	Post-optimization safety factor
E-E'	26°	0°	26°	1.216
W-W'	44°	-1°	43°	1.217
N-N'	46°	0°	46°	1.211
N1-N1'	44°	0°	44°	1.212
S-S'	47°	-1°	46°	1.215

5. Conclusions and Recommendations

Based on the stability analysis results of the final slope, it can be observed that:The safety factors of sections N-N′, N1-N1′, and S-S′ are close to the required standard values. Therefore, safety control measures are recommended for these three sections.For the other sections, debris removal, hazard elimination, and local reinforcement are required.

According to field observations, the mining area contains numerous hazardous rocks and loose boulders. Influenced by fault structures and joint fissures, unstable structural planes (or combinations thereof) exist in the slope bodies of various sections of the main mining area, which may lead to occurrences such as rockfall or local wedge-shaped failures in some bench slopes.

For localized fractured zones or areas with well-developed joint fissures, a local cable anchor reinforcement scheme is recommended. The specific cable anchor design is as follows:For locally unstable benches, four rows of cable anchors are installed from bottom to top.Horizontal spacing of anchors: 3.0 m.Vertical spacing of anchors: 3.75 m.Anchor length: 35 m.Installation angle: 15°.Cable anchors consist of 6×7Φs15.2 steel strands with a borehole diameter of 130 mm.Grouting material: P.O42.5 pure cement slurry. Designed anchor tensile capacity: ⩾ 600 kN.

This study analyzes the stability of slopes in an open-pit non-metallic mine and investigates various factors affecting slope stability. Stability analysis is not only related to safety concerns but also to social and economic benefits. Therefore, greater emphasis should be placed on slope stability analysis in open-pit mines to ensure multi-faceted benefits.

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