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Article

Risk Assessment of Geological Hazards on Steep Mine Slopes Using the Factor Weighting Method

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Abstract: This study focuses on three historically existing steep slopes (the Xintangpo, Wanxin, and Wanshun pits) in the Xintangpo mining area of Hunan Taojian Southern Cement Co., Ltd. In accordance with the Code for Geological Hazard Risk Assessment and relevant technical guidelines of Hunan Province, a risk assessment for landslides and rockfalls was conducted using the factor-weighting method, based on field geological surveys at a scale of 1:2000. The total area of the assessment zone is 58.0 hm². The geological environment is classified as moderately complex, the construction project is deemed important, and the assessment level is grade 1. The current status assessment indicates a small landslide (1.75×10^4 m³) in the northern part of the Xintangpo pit and a small rockfall (0.3×10^4 m³) in the southern part of the Wanshun pit, both of which pose low risk. The prediction and assessment comprehensively considered factors such as geotechnical properties, topographic slope conditions, rock stratum dip-angle, human activities, and rainfall. The results show that the landslide probability index N values for each block range from 4.20 to 6.75. Among these, Block A of Xintangpo (15,300 m²) has an N value of 6.75, indicating moderate risk; the N values for the remaining blocks are all less than 6.0, indicating low risk. Factor contribution analysis indicates that topographic slope conditions and the relationship between rock layer dip and slope aspect are the primary controlling factors for landslides, with a combined contribution rate of 52.3%. The comprehensive assessment classifies Block A of Xintangpo as a zone with moderate risk of landslides and rockfalls, while the remaining areas are classified as low-risk zones (total area: 71,800 m²). The evaluation of suitability for construction land indicates that Block A of Xintangpo is generally suitable, and the site as a whole is generally suitable. It is recommended that comprehensive measures, including slope reduction to reduce load, drainage systems, and anti-slide piles, be prioritized for this block.

Keywords: Geohazard risk assessment; steep slopes; factor weighting method; landslides; risk zoning

1. Introduction

Due to complex geological structures and rock types, coupled with a warm and humid climate, the hilly and mountainous regions of southern China are rich in mineral resources [1,2]. Open-pit mines are quite common in these regions. Although mining activities contribute significantly to national economic development, the steep slopes formed by mineral resource development often pose safety hazards to mining operations and ecological restoration due to complex geological conditions and unclear deformation mechanisms, and they also trigger geological and environmental issues such as landslides [3]. Limestone mining at the Xintangpo mining area of Hunan Taoxia Southern Cement Co., Ltd. began in the 1980s and 1990s. After years of small-scale mining, three mining rights were consolidated in 2015. There are currently three steep slopes within the mining area formed by historical mining activities: the Xintangpo Pit Slope, the Wanxin Pit Slope, and the Wanshun Pit Slope. Mining activities have disrupted the natural balance of the mining area and caused severe damage to geological structures [4,5], soil and vegetation [6,7], and water resources [8-10]. These slopes directly affect the safety of transportation routes within the mining area and the stability of the final slopes, making it urgent to conduct a geological hazard risk assessment to provide a scientific basis for subsequent remediation efforts.

The primary objective of this study is to assess the risk of geological hazards, specifically landslides and rockfalls, on three steep slopes in the Xintangpo mining area. To achieve this, a semi-quantitative factor-weighting method was employed, guided by national and provincial technical codes. Based on detailed 1:2000 scale field surveys, this study calculates a landslide probability index (N) for each slope block, identifies key contributing factors, and provides risk-based zoning. The findings are intended to support risk management and guide the design of targeted engineering interventions.

2. Study Area

The assessment area is located in Huishangang Town, Taojian County, Yiyang City, Hunan Province. Three steep slopes are scattered on the western, northern, and southeastern sides of the Xintangpo mining area. The geographical coordinates of the Xintangpo pit are 112°15’8.3”–112°15’21.9” E, 28°16’34.9”–28°16’51.1” N; the Wanxin pit is located at 112°15’30.8”–112°15’36.7” E, 28°16’46.7”–28°16’58.8” N; the Wanshun mining pit is located at 112°15’38.8”–112°15’51.4”E, 28°16’24.7”–28°16’35.8” N. Transportation access is convenient.

The three steep slopes were all formed by decades of mining operations at the original mine. The steep slope at the Xintangpo pit is classified as a Grade 1 slope; its base consists of a mine haulage road, with the bottom platform elevation ranging from approximately 80 m to 100 m. The slope is approximately 30 to 40 m high and 640 m long. The overall topography slopes from west to east. The highest elevation within the assessment area is approximately 138 m, located at the summit of a hill on the western side of the Xintangpo pit’s steep slope. The lowest elevation is approximately 51 m, corresponding to the water level of the pond at the base of the slope. The maximum relative elevation difference is 87 m, with a range exceeding 50 m; the ground slope primarily ranges from 10° to 40°.

The steep slope of the Wanxin pit is classified as a Grade 1 slope. The slope base consists of a mine haulage road, with the bottom platform elevation ranging from approximately 90 to 95 m. The slope height is approximately 30–50 m, and the length is approximately 430 m. The overall topography slopes from west to east. The highest elevation within the assessment area is approximately 146 m, located at the summit of a hillock on the western side of the top of the Wanxin Pit steep slope. The lowest elevation is approximately 48 m, corresponding to the water level of the pond at the base of the slope. The maximum relative elevation difference is 98 m, with a range exceeding 50 m; the ground slope primarily ranges from 10° to 40°.The steep slope of the Wanshun pit is a Class III slope, with a height of approximately 50–80 m and a length of approximately 480 m. The elevation of the bottom platform is approximately 50 m, and the width of the intermediate platform is approximately 15 m, with an elevation of approximately 70 m. The overall topography slopes from east to west. The highest elevation within the assessment area is approximately 158 m, located at the summit of a hillock on the eastern side of the top of the Wanshun pit’s steep slope. The lowest elevation is approximately 50 m, corresponding to the elevation of the platform at the base of the slope. The maximum relative elevation difference is 108 m, exceeding 50 m, with ground slopes primarily ranging from 10° to 40°. In summary, the terrain and landform category is classified as moderate.

The assessment area is located on the northern flank of the axial zone of the Huishan Port compound syncline. This compound syncline is an east-west-trending fold formed during the Indosinian period, covering an area of 800 km². No significant regional fault structures have been observed within the assessment area; neotectonic activity is primarily manifested as periodic, uneven uplift, with no signs of significant recent activity. According to GB 18306-2015, "Map of Peak Ground Acceleration Zones in China," the peak ground acceleration in the assessment area is 0.05 g, with a characteristic period of 0.35 s in the seismic response spectrum. The corresponding basic seismic intensity is VI, and the regional crustal stability is classified as stable. The regional geological background is simple.

According to the "Report on the Verification of Limestone Reserves for Cement Production at Xintangpo, Huishangang Mining Area, Taojian County, Hunan Province" (2019), the strata distributed within the assessment area include: the Quaternary (Q), the Middle-Upper Carboniferous Hutian Group ($C_{2+3}ht$), and the Lower Permian Maokou Formation (P_1m). The Middle-Upper Carboniferous Hutian Group ($C_{2+3}ht$) and the Lower Permian Maokou Formation (P_1m) are in angular unconformity contact. Based on historical drilling data, karst cavities are present but their development weakens with depth. The development of karst is constrained by tectonic, lithological, and hydrogeological conditions. While lithological and facies variations are minimal, most surface areas are covered by Quaternary deposits of considerable thickness. The rock and soil structure is relatively complex, and the engineering geological properties are poor. Therefore, the stratigraphic lithology and engineering geological properties of the assessment area are classified as moderate. (For the project location and surrounding terrain, refer to Figure 1-2: Satellite imagery of the assessment area and photographs of the various slopes.)

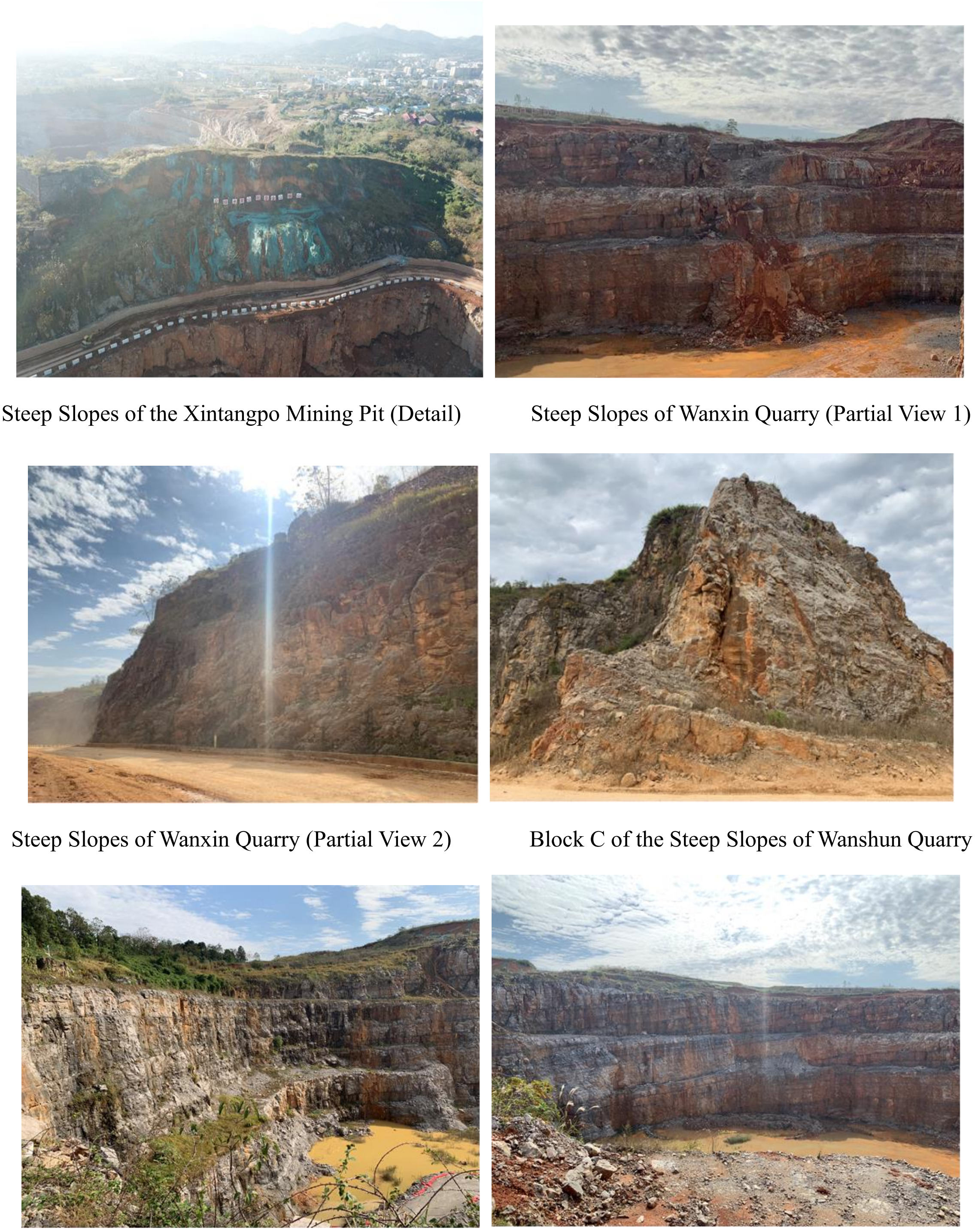
Fig. 1. Satellite Image of the Assessment Area.

Steep Slopes of the Wanxin Mining Pit

Steep Slopes of the Wanshun Mining Pit

Landslide Hazard Site in Block A of the Steep Slopes of the Xintangpo Mining Pit

Rockfall Hazard Site in Block E of the Steep Slopes of the Wanshun Mining Pit



Steep Slopes of the Xintangpo Mining Pit (Detail) — Steep Slopes of Wanxin Quarry (Partial View 1)

Steep Slopes of Wanxin Quarry (Partial View 2) — Block C of the Steep Slopes of Wanshun Quarry

Block D of the Steep Slopes of Wanshun Quarry — Steep Slopes of Xintangpo Quarry

Fig. 2. Photographs of the steep slope assessment area (Note: Grid lines have been removed from the image per reviewer request).

3. Materials and Methods

3.1 Evaluation Process

The assessment procedure comprised five sequential stages: (1) data collection, involving the review of existing geological reports, mining plans, and topographical maps; (2) comprehensive field surveys, utilizing 1:2000 topographic maps to document geological features and existing hazards; (3) current status assessment, evaluating the type, scale, and stability of existing geological hazards; (4) predictive assessment, employing the factor-weighting method to forecast the likelihood of future landslides and rockfalls; and (5) comprehensive zoning assessment, integrating current and predictive results to determine overall risk levels and construction land suitability, culminating in report preparation.

3.2 Field Survey Methods

Using 1:2000 topographic maps as the base map, a comprehensive geological hazard survey was conducted within an 80–120 m radius around three steep slopes. The survey involved detailed field mapping and documentation. Data collection included the measurement of slope geometries (height and angle using laser rangefinders), identification of lithological boundaries through outcrop inspection, and assessment of rock mass structure characteristics (joint spacing, weathering degree). Specifically, we documented types, scale, distribution characteristics, formation conditions, stability, and severity of existing geological hazards; geological features, including stratigraphic boundaries, lithology, and drainage systems; sites of human engineering activities, such as previous mining excavations and haul roads; and water sources, including private wells and ponds.

3.3 Factor-Weighting Method

In accordance with Appendix H of the Key Points for the Preparation and Review of Geological Hazard Risk Assessment Reports in Hunan Province, the factor-weighting method is used to conduct a semi-quantitative assessment of the likelihood of landslides and rockfalls. The term semi-quantitative refers to the conversion of qualitative field observations into numerical scores (3, 6, 9) based on predefined categories, which are then aggregated using statistically or empirically derived weights (w_i). Unlike purely qualitative descriptions, this method provides a numerical index (N) for comparison, but it does not involve rigorous physical-mechanical modeling. The factors, their weights, and scoring criteria were derived from this provincial technical guideline.

3.3.1 Landslide Probability Assessment Model

The formula for calculating the landslide probability index N is:

$$N = \sum_{i=1}^{6} w_i \cdot k_i \qquad (1)$$

Here, wi represents the weight of the i-th factor, and ki represents the scale score (where ki ∈ {3, 6, 9}). See Table 1 for the definitions of each factor, their weights, and the scale score standards.

Table 1. Factors for assessing landslide risk and scoring criteria.

Factor	Description	Weight w_i	Scale Score k_i Assessment
A	Rock and Soil Properties and Thickness	0.15	9: Loose rock and soil, thickness > 10 m 6: Relatively loose rock and soil, thickness 5–10 m 3: Relatively hard rock, thickness < 5 m
B	Degree of Deformation and Stability of Rock and Soil	0.15	9: Highly fractured, numerous cracks, poor stability 6: Moderately fractured, signs of deformation 3: No obvious deformation, relatively stable
C	Topographic conditions for slope cutting	0.20	9: Slope height > 16 m, slope angle > 45° 6: Slope height 8–16 m, slope angle 25–45° 3: Slope height <8 m, slope angle <25°
D	Relationship between rock dip and slope aspect	0.20	9: Downslope 6: Oblique slope 3: Uphill slope
E	Disaster-causing factors related to human economic activities	0.15	9: Frequent activities, many disaster-causing factors 6: Fairly frequent activities, many factors 3: Infrequent activities, few factors
F	Frequency and intensity of heavy rainfall	0.15	9: Frequent occurrences, high intensity 6: Fairly frequent occurrences, moderate intensity 3: Infrequent occurrences, low intensity

Criteria for Assessing Landslide Risk:

$$Risk\ Level\ = \begin{cases} High & N \geq 7 \\ Moderate & 4 < N < 7 \\ Low & N \leq 4 \end{cases} \quad (2)$$

3.3.2 Model for Assessing the Likelihood of Rockfall

The rockfall likelihood index employs a similar model, with factors focusing on rock mass structure, overhang conditions at the rockfall front, and other factors. The factors, weights, and scoring criteria are detailed in Table 2. The risk level criteria are the same as in Equation (2).

Table 2. Factors for assessing the likelihood of rockfalls and scoring criteria.

Factor	Description	Weight	Scale Score Assessment
A	Rock and Soil Properties and Thickness	0.15	9: Loose rock and soil, thickness > 30 m 6: Moderately loose rock and soil, thickness 10–30 m 3: Relatively hard rock and soil, thickness < 10 m
B	Geological structure	0.15	9: Alternating hard and soft rock types; fractured structure 6: Relatively fractured rock mass; few joints 3: Intact rock mass; no joints or fractures
C	Terrain Slope Conditions	0.20	9: Overhanging edge, slope > 55°, elevation difference > 30 m 6: Overhanging edge, slope > 45° 3: Overhanging edge, slope < 45°
D	Relationship Between Strata Trend and Slope Direction	0.20	9: Down-dip slope 6: Cross-dip slope 3: Up-dip slope
E	Disaster-causing factors related to human economic activities	0.15	9: Severe damage, slope > 60° 6: Excavation creating a weak foundation 3: Low activity, with slope protection
F	Hydrometeorology	0.15	9: Abundant rainfall, swift currents 6: Conditions conducive to heavy to torrential rain 3: No surface runoff

3.3.3 Principles for Comprehensive Hazard Zoning

Based on the results of comprehensive assessments of current conditions and future projections, the hazard levels for each zone are determined using the "higher-than-lower" principle:

$$R_{Overall} = Max(R_{Current}, R_{Forecast}) \quad (3)$$

where R ⊆ {low risk, medium risk, high risk}.

In this context, RCurrent is the risk level derived from the field investigation and evaluation of existing hazards (as per the classification in Table 3), representing the present state of risk. RForecast is the risk level predicted based on the calculated probability index N (from Equation 1 or the rockfall model) and the criteria in Equation (2). The overall risk ROverall is the higher of these two levels to ensure a conservative safety assessment.

See Table 3 for the geohazard risk classification standards.

Table 3. Geological hazard risk classification table.

Development Level[1]	Severity of Impact	Triggering Factors	Risk Level
Strong development	High risk	Natural, human-induced	High risk
Strong development	Moderate risk	Natural, human-induced	High risk
Moderate development	High risk	Natural, human-induced	High risk
Strong development	Low risk	Natural, human-induced	Moderate risk
Moderate development	Moderate risk	Natural, human-induced	Moderate risk
Weak growth	High risk	Natural, human-induced	Moderate risk
Moderate growth	Low risk	Natural, human-induced	Low risk
Weak growth	Moderate risk	Natural, human-induced	Low risk
Weak growth	Low risk	Natural, human-induced	Low risk

[1] **Note:** Development level refers to the degree of geological hazard activity or prevalence in the area, ranging from strong development (active, frequent hazards) to weak growth (rare or inactive hazards).

3.3.4 Classification of Suitability for Construction Land

In accordance with Table 37 of the "Code for Assessment of Geological Hazard Risks"(GB/T 40112-2021), the suitability of construction land is classified into three levels (Table 4).

Table 4. Classification of suitability for construction land.

Level	Classification Description
Suitable	The geological environment is relatively simple; the likelihood of construction projects triggering geological hazards is low; the likelihood of construction projects
	being affected by geological hazards is low; the risk is low; and issues are easy to address
Generally Suitable	Geological hazards are moderately developed; geological structures and stratigraphic lithologies vary significantly; the likelihood of construction projects triggering geological hazards is moderate; the likelihood of construction projects being affected by geological hazards is moderate; the risk level is moderate, but measures can be taken to address the issue.
Poor Suitability	Geological hazards are prevalent, geological structures are complex, construction projects are highly likely to trigger geological hazards, and construction projects are highly susceptible to geological hazards; the risks are high, and prevention and mitigation are difficult.

4. Results and Analysis

4.1. Assessment of the Current Status of Geological Hazards

1. Xintangpo Mining Pit Assessment Area

Based on field investigations and a review of historical records, a small landslide has been identified in the northern part of the Xintangpo mining pit assessment area. The landslide is located on the northern slope, with a cover layer approximately 20 m thick overlying Carboniferous Hutian Group limestone. The slope is approximately 35 m high with a gradient of about 40°. The volume of the landslide mass is approximately 1.75×10^4 m³. This is classified as a small-scale event and has not resulted in any casualties or property damage. The current stability is relatively poor. No other geological hazards were identified. The current risk level (R_Current) for this area is assessed as low.

2. Wanxin Pit Assessment Area

No geological hazards such as landslides, rockfalls, debris flows, ground fissures, ground collapse, or ground subsidence were identified within the Wanxin pit assessment area. The current risk level (RCurrent) is low.

3. Wanshun Pit Assessment Area

A small-scale rockfall occurred in the southern part of the Wanshun pit assessment area. This rockfall is located on the southern slope, where the rock type consists of Carboniferous Hutian Formation limestone. The slope is approximately 70 m high with a gradient of about 60°. The rockfall volume is approximately 0.3×10^4 m³, classified as small in scale, and has not resulted in any casualties or property damage. No other geological hazards were identified. The current risk level (R_Current) for this area is assessed as low.

4. Conclusions of the Current Status Assessment

In summary, the current risk levels across the three pits are low. A summary of the current status assessment results is presented in Table 5.

Table 5. Classification of current status assessment results.

Assessment Area	Type of Geological Hazard	Development Level	Severity Level	Risk Level
Xintangpo Quarry	Landslides	Moderate	Minor	Minor
	Other types	Not developed	Minor	Minor
Wanxin Mine Shaft	Various hazards	Underdeveloped	Minor	Minor
Wanshun Mine Shaft	Collapse	Moderate	Minor	Minor
	Other types	Underdeveloped	Minor	Minor

4.2 Predictive Assessment and Comprehensive Zoning

Using the factor-weighting method described in Section 3.3, the landslide probability index N was calculated for each slope block. The calculated N values for each block ranged from 4.20 to 6.75. Block A of Xintangpo had the highest N value (6.75), indicating moderate risk. The N values for the remaining blocks were all less than 6.0, suggesting low risk.

Based on the results of the comprehensive assessment of current conditions and the predictive assessment, comprehensive hazard zoning is conducted according to the higher-than-lower principle. The results of the comprehensive zoning are shown in Table 6.

Table 6. Results of comprehensive zoning for geological hazard risk.

Location	Area (m²)	Geological Environment	Development Level	Current Hazard Level	Predicted Hazard Level	Overall Hazard Level
Xintangpo Block A	15,300	Moderate	Moderate	Moderate	Moderate	Moderate
Xintangpo Block B	14,200	Moderate	Weak	Low	Low	Low
Wanxin District	25,000	Moderate	Weak	Low	Low	Low
Wanshun Block C	11,700	Moderate	Weak	Low	Low	Low
Wanshun Block D	12,600	Moderate	Weak	Low	Low	Low
Wanshun Block E	8,300	Moderate	Moderate	Low	Low	Low

Areas with moderate risk of landslides and rockfalls are located in Block A of the Xintangpo mining pit, covering an area of 15,300 m² which accounts for 51.9% of the total slope area at Xintangpo. This zone features a mixed rock-soil slope with an approximate gradient of 45° and a downslope structure. Small-scale landslides are currently active in the area. The predicted risk of triggering landslides and rockfalls is moderate, with potential hazards to ore transport vehicles, personnel, and roads; the hazard level is classified as moderate.

Geological hazard risk sub-zones cover a total area of 71,800 m², including Block B of Xintangpo (14,200 m²), the entire Wanxin area (25,000 m²), Block C of Wanshun (11,700 m²), Block D of Wanshun (12,600 m²), and Block E of Wanshun (8,300 m²). Currently, geological hazards in this area are either absent or present at a low level. The predicted risk of triggering geological hazards is low, and the hazard level is low.

4.3 Factor Contribution Analysis

To identify the primary factors influencing landslide risk, an analysis of the contribution rates of each factor was conducted using the following formula:

$$Contribution\ rate_i = \frac{w_i \cdot k_i}{N} \times 100\% \tag{4}$$

Taking Block A of Xintangpo (N=6.75) as an example, the contribution rates of each factor are shown in Table 7.

Table 7. Analysis of factor contribution rates for block A of Xintangpo.

Factor	Weight w_i	scale k_i	Weighted value	contribution rate (%)
A	0.15	9	1.35	20.0
B	0.15	6	0.90	13.3
C	0.20	9	1.80	26.7
D	0.20	9	1.80	26.7
E	0.15	3	0.45	6.7
F	0.15	3	0.45	6.7
Total	1.00	-	6.75	100.0

The analysis indicates that the combined contribution of topographic slope conditions (C) and the relationship between rock dip and strike (D) accounts for 53.4%, making them the primary controlling factors for landslide risk; geotechnical properties (A) account for 20.0%, making them a secondary factor; while the contribution of deformation degree (B), human activities (E), and precipitation (F) is relatively low. These results are highly consistent with the actual geological conditions of the slope—Block A of the Xintang Slope is a down-dip, steeply cut slope, possessing favorable geometric conditions for landslide formation.

5. Discussion

This study employed the factor weighting method to conduct a geological hazard risk assessment of three historically existing steep slopes in the Xintangpo mining area. The results demonstrate that this method can effectively integrate multiple influences of factors and provide a semi-quantitative risk classification for each block. The landslide probability index (N) for Block A in Xintangpo is 6.75, which is close to the threshold for high risk (7.0) and aligns with the location of the existing landslide, thereby validating the reliability of the assessment results. The N values for the remaining blocks range from 4.20 to 5.85. Although these values mathematically fall within the moderate risk category (Equation 2), a comprehensive assessment that integrates predictive indices with site-specific observational data reasonably classifies these areas as low-risk zones.

Factor contribution analysis reveals that topographic cutting and the relationship between rock strata dip and slope aspect are the primary controlling factors for landslide risk, with a combined contribution rate of 52.3%. This finding is consistent with other studies on slope stability in similar geological contexts, which often identify slope geometry and structural controls as dominant factors [e.g., 11,12]. In Block A of Xintang Slope, both factors reached the highest scale score (9 points), explaining the elevated risk. In contrast, Block E of Wanshun, despite also having a downslope structure (D = 9), had a lower N-value (5.40) due to its rock slope composition and absence of thick overburden (A = 3). This underscores the moderating influence of geotechnical properties, a finding that echoes the multi-factor interaction emphasized in the work of Cruden and Varnes [13].

Regarding the weight assignment used in this study, the values (0.15 to 0.20) are derived from provincial guidelines specific to Hunan Province and reflect empirical regional experience. In comparison, broader literature on slope susceptibility often assigns slightly higher weights to hydrological factors (e.g., 0.25) in tropical residual soil settings [14]. The lower weight for rainfall in this study (0.15) is appropriate given the site's moderate precipitation patterns and the fact that the primary failure mechanisms are structurally controlled rather than purely rainfall-induced. This comparison highlights the site-specific nature of the factor-weighting approach.

Regarding methodological limitations, the factor weighting method, while practical, is a static, semi-quantitative assessment. It does not account for time-varying effects such as the progressive deterioration of rock strength due to weathering or the transient impact of extreme rainfall events [15]. Furthermore, the assignment of weights, though based on established provincial guidelines, still involves a degree of expert judgment and may not fully capture site-specific complexities. Future studies should aim to integrate this approach with dynamic models, incorporating real-time automated monitoring data (e.g., rainfall, pore water pressure, displacement) to develop a more robust, time-dependent risk forecasting system .

6. Conclusions

This study successfully assessed the risk of landslides and rockfalls on three steep mine slopes in the Xintangpo mining area using the factor weighting method, based on detailed field surveys and established technical guidelines.

The comprehensive assessment classified Block A of Xintangpo as a moderate-risk zone (area: 15,300 m^2) for landslides and rockfalls, while the remaining areas, totaling 71,800 m^2, were classified as low-risk zones. This detailed zoning provides a clear spatial basis for targeted risk management.

Factor contribution analysis identified topographic slope conditions and the relationship between rock strata dip and slope aspect as the primary controlling factors for landslides, with a combined contribution rate of 52.3%. Geotechnical properties were a secondary factor, contributing 20.0%.

Based on the risk assessment, the suitability of Block A of Xintangpo for construction land was rated as generally suitable, while the remaining low-risk areas were rated as suitable. The overall site suitability is generally suitable.

For the moderate-risk Block A of Xintangpo, it is recommended that comprehensive remediation measures be prioritized, including slope cutting to reduce load, the implementation of an effective drainage system, and the installation of anti-slide piles. For low-risk areas, a system of regular inspections and deformation monitoring is advised to prevent risk escalation.

The uniqueness of this study lies in its application of a semi-quantitative, code-based factor-weighting method to a specific post-mining landscape, providing a practical and replicable framework for risk assessment in similar contexts. The findings offer direct, actionable guidance for mine site remediation and safety management. Future research should focus on integrating dynamic, real-time monitoring data to enhance the predictive accuracy and temporal resolution of such risk models.

Supplementary File: It is available online at www.iikii.com/ijesp/xxx/s001.

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