Analysis, Assessment, and Remediation of Highway Rockfall

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Abstract： Preventing geological disasters such as highway rock collapses is crucial for ensuring traffic safety and social stability. Traditional research often relies on on-site investigations to identify collapses, which can delay the remediation process. In this study, we focused on a highway rock collapse case in Shuangfeng Town, Longchang City. Using a combination of remote sensing imagery analysis, on-site verification, and surveying, we comprehensively obtained the geological characteristics and surrounding environmental information of the dangerous rock mass. Through detailed analysis of the lithology, structure, weathering degree, and other features of the dangerous rock mass, and considering geological structures, climatic conditions, human activities, and other internal and external factors, we explored the formation mechanism of the rock collapse in depth. Subsequently, we assessed the potential threat level of the dangerous rock mass to provide a scientific basis for the design of the remediation plan. The results indicate that the dangerous rock mass in this area is primarily composed of gray thick-bedded to blocky fine-grained sandstone from the Middle Jurassic Shaximiao Formation, with two sets of steeply dipping "X" joints. Stability analysis reveals that under natural conditions, the dangerous rock mass is relatively stable, but its stability significantly decreases under heavy rainfall conditions, becoming unstable. Based on these findings, we proposed a "manual rock clearance" plan. Testing confirmed that this plan.achieved the intended goals and ensured the safety of the area.

Keywords: Remote sensing; collapse; deformation characteristics; stability

1. Introduction

A rockfall is a rock mass on a steep slope, cut by several sets of structural planes. Under the influence of gravity, earthquakes, and pore water pressure, it gradually separates from the parent rock, becoming unstable and prone to collapse. Driven by geological and external factors, rockfalls can take forms like falling, sliding, and rolling, acting alone or in combination[1-2].Rockfalls can cause significant economic losses or injury to people[3-4].Rockfall disasters frequently occur along highways, posing a serious threat to traffic safety and the lives and property of nearby residents. This has become a crucial issue that urgently needs to be addressed in transportation infrastructure and operations[5-6].In recent years, researchers have made significant progress in studying highway rockfalls. On the Duwen Highway from Dujiangyan to Yingxiu, Qu Yongping investigated the characteristics and mechanisms of post - earthquake geological hazards, assessing their impact on the highway and informing post - disaster relief and prevention[7].Naman Maimaiti and others modified a shaking table to conduct model tests on the failure of steep - cliff block rockfalls under seismic action[8].Chen Xiaogang and others studied five rockfalls at K1515 of the Shanghai - Chengdu Expressway. Through field surveys, statistics, and analysis, they clarified the engineering geological conditions and deformation characteristics of the rockfall areas[9].In rockfall research on highways, traditional methods like field surveys and numerical simulations are widely used[10-13].The emergence of UAV - based surveying technology has provided a new tool for rockfall research. It enables rapid acquisition of high - precision topographic and geological data, improving research efficiency and accuracy[14-15].

In recent years, researchers have made notable achievements in highway rockfall studies. However, most current highway rockfall research relies on field surveys, which have limitations in complex terrains, such as incomplete coverage of potential rockfall areas and insufficient detailed analysis of individual rockfalls. To address these limitations, remote - sensing technology has been introduced into rockfall research. It offers advantages like large - scale, long - duration, high - timeliness, and three - dimensional monitoring, enabling rapid acquisition of high - precision topographic and geological data, and significantly enhancing research efficiency and accuracy. This study will employ a comprehensive approach combining field surveys and remote - sensing technology to investigate highway rockfall disasters. By analyzing remote - sensing images, potential rockfall areas can be identified in advance, compensating for the shortcomings of field surveys and enabling detailed analysis of individual rockfalls. Additionally, drawing on relevant research findings, targeted remediation strategies will be proposed to provide more scientific and effective theoretical support and technical guidance for highway rockfall prevention and control.

1 Regional Characteristic Analysis and Remote Sensing Identification

1.1 Natural Conditions

The collapse - prone area has a subtropical continental warm - humid monsoon climate, featuring warm and humid weather, hot summers, abundant rainfall, and concurrent rain and heat. Natural disasters likeheavy rain, floods, strong winds, and hailstorms occur. The annual average precipitation is 1066.7 mm, with most rainfall concentrated in the rainy season from May to September, accounting for 73.7% of the yearly total. The survey area is located in the middle reaches of the Tuojiang River system in the Yangtze River Basin, where surface water systems are underdeveloped.

1.2 Topography and Landform

The collapse - prone area features a hilly landform in central - southern Sichuan with a landscape sloping from east to west. The highest point is a mountain peak in the southeast of the survey area at an elevation of 418 m, while the lowest point is below a slope in the northwest at 351 m, creating a relative height difference of 67 m. The slope is a reverse slope, dipping west - northward at 16° - 26°, gentler at the bottom and steeper at the top. It is relatively straight and uniform with well - developed vegetation. Due to the landform and differential weathering of rock layers, a steep cliff has formed at the top of the slope, with dangerous rock masses developing above the slope shoulder adjacent to the highway.

1.3 Collapse Identification

Collapses typically occur on steep slopes and canyon walls composed of jointed and fissured hard rocks. These thick - bedded hard rocks form steep slopes and often have two or more sets of steeply dipping joints, one of which, parallel to the slope face, often evolves into tension fractures. The three fundamental conditions for collapse development are terrain, geological structure, and lithology. When interpreting collapses, focus on three key aspects: tone, location of development, and texture.

(a)Remote Sensing Image (b)Site of Dangerous Rock Mass

Figure 1 (a) Remote Sensing Image; (b) Site of Dangerous Rock Mass

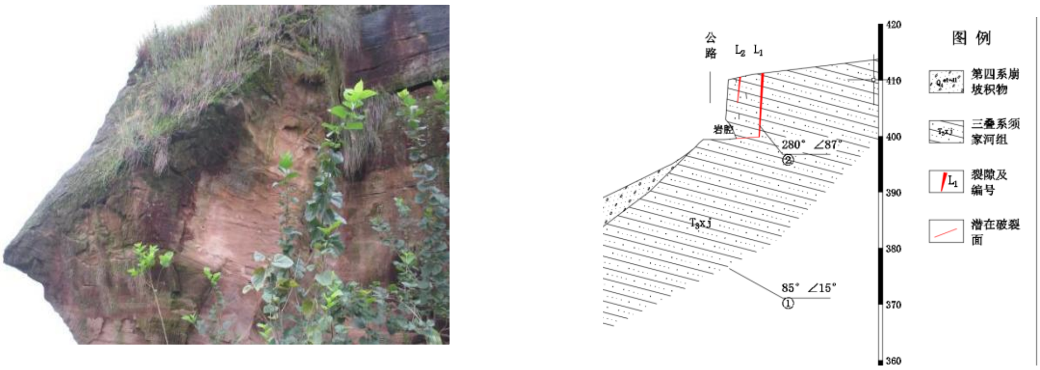
Combining the above info and Figure 1, the collapse site is on a hillside. The collapse mass has a rough, uneven surface. Scree of various sizes is piled at the slope's foot, with little or no vegetation. The terrain is higher in the east and lower in the west. The slope is steep at the top and gentle at the bottom, and the overall slope is relatively straight and uniform, with well - developed vegetation. From the site photo, the deposit at the lower slope is conical, lacking obvious vegetation, indicating high freshness of the collapse deposits. This shape is usually a direct result of a collapse event. The steep rock walls and fractures on the upper slope further confirm this. These fractures and exposed rock faces are consistent with collapse characteristics, so this area can be identified as a collapse zone.

2. Dangerous Rock Mass Characteristics and Deformation Mechanism

2.1 Basic Morphological Characteristics of the Dangerous Rock Mass

The dangerous rock mass is located on the eastern slope of the survey area. The slope is a reverse slope, steep at the top and gentle at the bottom, with a steep cliff formed at the slope shoulder. It mainly consists of grey thick - bedded to blocky fine - grained sandstone from the Middle Jurassic Shaximiao Formation, with a dip of 85°∠15°, and the rock is hard. The middle and lower parts of the slope are covered by Quaternary Holocene slope deposits and residual deposits, mainly consisting of silt and clayey silt with a small amount of boulders. The vegetation on the slope is relatively lush, mainly consisting of trees and shrubs, while the slope top is gentler, mainly with herbaceous plants (Figure 2(a)).

The dangerous rock mass is approximately triangular in plan view and rectangular in elevation. It has a base height of 397.1 m, a top height of 408.4 m, a height difference of 11.3 m, a width of 7.4 m, a length of 13.4 m, and a volume of 588 m³, classifying it as a super - large dangerous rock mass. Two sets of steeply dipping "X" joints control the development and deformation of the dangerous rock mass. Joint ① has a dip of 15°∠88°, a joint density of about 3.2 m per joint, is closed, short - extending, with a smooth joint surface and poor combination, classified as a hard structural surface. Joint ② has a dip of 280°∠87°, a joint density of 1.8 m per joint, is slightly open, long - extending, with a smooth joint surface, slightly rough, partially filled with weathered soil, and poor combination, also classified as a hard structural surface. Parallel to Joint ②, there are two tension fractures, L1 and L2, which both penetrate the dangerous rock mass in plan view. In profile, L1 penetrates the entire dangerous rock mass. L1 is 2 - 8 cm wide, while L2 is less than 3 cm wide and disappears (Figure 2(b)).



(a) (b)

Figure 2 (a)Morphological characteristics of hazardous rock mass;(b)Geological Profile of Dangerous Rocks

2.2 Analysis of Formative Factors

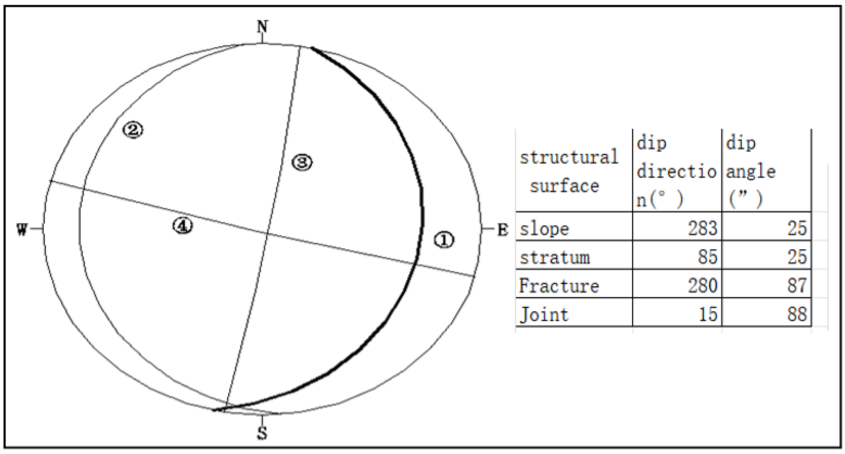
2.2.1 Dominant Factors (Internal Causes)

(1) Geological Structure

The region has intense geological structures with well - developed tectonic fractures. Located on a steep slope shoulder, the rock mass, under long - term stress, turns the tectonic fractures into unloading fractures, reducing the rock's integrity. These fractures provide favorable boundaries for deformation and failure, worsening instability.

(2) Rock Mass Structure

Rockfalls occur along weak structural planes within the rock mass. There are three main sets of structural planes (Fig. 3) with dips of ①85°∠15°, ②280°∠87°, and ③15°∠160°, with widths of 0 - 80 mm. Some fractures are filled with weathered soil. L1 is almost through, and L2 is connected at the top. Under the rock's self - weight, compression or plastic flow widens the steep fractures, causing stable rock to become potentially unstable and leading to collapse.



structural surface	dip direction(°)	dip angle (”)
slope	283	25
stratum	85	25
Fracture	280	87
Joint	15	88

Fig 3.Stereoscopic projection of structural plane and slope surface

2.2.2 Triggering Factors (External Causes)

(1) Weathering

The main lithology of the rock mass is fine sandstone of the Shaximiao Formation, with quartz, feldspar, and rock fragments as the main components. The structure and composition make the structural surface susceptible to weathering and erosion, further widening joints and reducing rock mass integrity.

Atmospheric

Precipitation: Rainwater infiltration promotes weathering. Sudden static water pressure from fracture water significantly impacts rock mass stability, erodes fractures, and softens the base, accelerating deformation and failure.

Seismic Activity

Earthquakes release huge energy, violently shaking mountains and vibrating the ground. This expands slope fractures and weathering unloading fractures, causing rock mass loosening, breaking, and disintegration, destroying mountain stability and causing collapses and falling rocks.

Human Engineering Activities

The foot of the steep cliff where the dangerous rock develops is a highway. Excavating the slope foot forms a rock cavity, destroying the original stress state of the rock mass, and adversely affecting the stability of the dangerous rock mass.

2.3 Analysis of Deformation and Failure Mechanism

The potential failure mode of the dangerous rock is overturning. It develops in thick - to - blocky fine - grained sandstone with a set of steep - dipping "X" joints. One set of steep - dipping joints nearly parallel to the slope and dipping steeply outward is under tension due to good unloading conditions, forming the rear boundary of the dangerous rock with an L1 tensile crack width of 8 cm. Another set of steep - dipping joints nearly perpendicular to the slope cuts the dangerous rock and forms its side boundaries. With the development of artificial cutting at the base and differential weathering forming rock cavities, the center of gravity of the dangerous rock tilts outward. Under gravity and pore water pressure, it overturns around the main controlling steep - dipping joint base, causing collapse.

3. Stability and Hazard Analysis and Evaluation

3.1 Analysis and Determination of Geotechnical Physical and Mechanical Parameters

Based on laboratory test data of geotechnical materials, relevant standards, and experience from nearby sites, suggested values for the physical and mechanical parameters of the rock mass are proposed (see Table 1).

Rock name	Density ρ（g/cm^3）	Tensile strength σ（MPa）
Slightly weathered sandstone	2.2	0.7

Table 1 Recommended values for physical and mechanical parameters of rock mass

Due to no site - testing conditions in the collapse survey area, based on detailed on - site investigations and indoor comprehensive analysis, the fine - grained sandstone joint surfaces are few, mostly flat, closed to slightly open, rough, and poorly bonded. According to the "Technical Code for Building Slopes" (GB50330 - 2002), the shear strength parameters of sandstone joint surfaces are: friction angle 18° - 27°, cohesion 50 - 90 kPa. Joint water pressure is determined based on joint water - holding capacity and rainfall.

3.2 Stability Calculation and Evaluation

3.2.1 Determination of Calculation Model and Method

The failure deformation mode of this dangerous rock mass is overturning - type, and the model is shown in the figure 4 below.

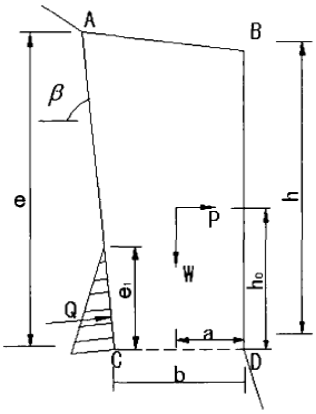


Figure 4. Calculation model for stability coefficient of toppling collapse

The calculation formula is as follows:

$$K = \frac{\frac{1}{3}[\sigma_t]\cdot b^2 + W\cdot a}{Ph_0 + Q\left[\frac{1 \;\; e_1}{3si\beta+} + b\cos\beta\right]} \qquad (1)$$

$$Q = \frac{1}{2}\gamma_W h_w^2 \qquad (2)$$

$$P = \zeta_e W \qquad (3)$$

K - stability coefficient of the dangerous rock;

W——Self - weight of the dangerous rock mass (unit length gravity in the extension direction, kN/m);

[σt]——Characteristic value of the tensile strength of the dangerous rock (kPa), determined by multiplying the standard tensile strength of the rock by a 0.4 reduction factor.

β——Rear - edge fracture dip angle (°)；

e1——Rear - edge fracture water - filling height (m)

a——horizontal distance from the center of gravity of the dangerous rock to the overturning point (m);

b——horizontal distance from the lower end of the unfractured part of the rear fracture to the overturning point (m);

h0——vertical distance from the center of gravity of the dangerous rock to the overturning point (m);

Q——static water pressure in the fracture (kN).

P——horizontal seismic force per unit length on the dangerous rock (kN);；

γw——unit weight of water, taken as 10 kN/m^3;

ζe——horizontal seismic coefficient, taken as 0.05 for rock - like landslides.

3.2.2 Calculation Conditions

The groundwater level in the survey area is deep, and the basic seismic intensity is ≤ VI degrees. Torrential rain is the main factor inducing the instability of dangerous rocks. According to the "Specification for Geological Disaster Prevention Engineering Reconnaissance" (DB50/143-2003), only the natural condition (Condition I) and the torrential rain condition (Condition II) are considered for the stability calculation of dangerous rocks:

Condition I: Self - weight, only considering the self - weight of the dangerous rock and additional loads;

Condition II: Self - weight + fracture water pressure, considering the fracture water pressure generated by torrential rain (the water - filling height of the fracture is taken as 1/3 to 1/2 of the fracture depth).

3.2.3 Calculation Results and Stability Evaluation of Dangerous Rocks

According to the "Specification for Geological Disaster Prevention Engineering Reconnaissance" (DB50/143-2003), a stability - assessment criterion for dangerous rocks is established (Table 2).

Dangerous rock type	stable state of dangerous rock			
	Unstable	unstable	basically stable	stable
Sliding dangerous rock	F＜1.0	1.00≤F＜1.15	1.15≤F＜Ft	F≥Ft
Inverted dangerous rock	F＜1.0	1.00≤F＜1.25	1.25≤F＜Ft	F≥Ft
Falling dangerous rock	F＜1.0	1.00≤F＜1.35	1.35≤F＜Ft	F≥Ft
Note: Ft is the safety factor for the stability of dangerous rocks, which is determined according to Table 3 based on the level and type of dangerous rock prevention and control engineering.				

Table 2 Stable State of Dangerous Rocks

Dangerous rock type	dangerous rock collapse prevention and control engineering level					
	Level 1		Level 2		Level 3	
	Non verification working conditions	verification working	Non verification working conditions	verification working	Non verification working conditions	verification working
Sliding dangerous rock	1.4	1.15	1.3	1.1	1.2	1.05
Inverted dangerous rock	1.5	1.2	1.4	1.15	1.3	1.1
Falling dangerous rock	1.6	1.25	1.5	1.2	1.4	1.15

Table 3 Safety Factors for Stability of Dangerous Rocks

According to the "Specification for Geological Disaster Prevention Engineering Investigation" (DB50/143-2003), this prevention and control project is classified as Grade III. Calculations using the formula show a stability coefficient of 1.442 for Condition I and 1.237 for Condition II. This indicates the dangerous rock mass is relatively stable in natural conditions but unstable in heavy rain, with storms being the main threat to its stability (Table 3).

3 Hazard Assessment of Dangerous Rocks

Site investigations reveal that a collapse caused by dangerous rock instability would directly endanger lives and property below, including a household of 8 people, 3 mu of farmland, 8 mu of forestland, and 30 meters of highway, with an estimated direct economic loss of 900,000 yuan. Highway disruption would cause immeasurable indirect losses.

4. Mitigation of Rockfall Hazards

4.1 Design Parameters for Mitigation

Table 4 Recommended values for physical and mechanical parameters of rock mass

rock name	Densityρ	compressive strength		tensile strengthσa	Standard value of cohesionC_k	Standard value of internal friction angle φ_k
		naturalR	saturationR_b			
Slightly weathered fine sandstone	2.2	18	10	0.7	1.8	44

In table 4, as no site testing is available in the survey area, on - site investigations and indoor analyses show that fine - grained sandstone joint surfaces are few, mostly flat, closed to slightly open, rough, and poorly bonded. According to the "Technical Code for Building Slopes" (GB50330 - 2002), the shear strength parameters of sandstone joint surfaces are: friction angle 18° - 27°, cohesion 50 - 90 kPa. Joint water pressure is determined based on joint water - holding capacity and rainfall.

4.2 Scheme Selection

Considering topography, deformation mechanisms, and construction conditions, the recommended mitigation strategy is hazard clearance to prevent further instability and collapse. Either of the following two schemes can be used:

Option 1: Directional Blasting Hazard Clearance

First, conduct a detailed geological survey and analysis of the dangerous rock mass to determine its structure, joints, and deformation. Then, develop a blasting plan based on the geological characteristics, including blast hole depth, spacing, and charge. Drill holes on the rock surface and arrange blast holes according to design requirements.

Option 2: Manual Hazard Clearance

Manually break and clear the dangerous rock mass layer by layer from the top, keeping each operation within a controlled range. Use professional tools like air hammers to gradually reduce the rock mass, strictly controlling the slope to no steeper than 1:0.2 to ensure slope stability and safety. During construction, use real - time monitoring equipment to record rock mass changes and prevent secondary sliding or collapse.

Manual hazard clearance avoids the vibration and flying - rock risks of directional blasting, effectively protecting the houses and people below the highway. Compared to blasting, it minimizes environmental disturbance, with noise and vibration controlled during construction. Although it takes longer than blasting, it is technically feasible with controllable risks. Although labor costs are higher, it avoids the potential risks and subsequent remediation costs of blasting. Overall costs are manageable, and as highway closure is unnecessary, residents' lives and production are not significantly disrupted, avoiding indirect economic losses.

Comprehensively, it is recommended to use Option 2, "Manual Hazard Clearance," for mitigation, and the design plan view is shown below figure 5.

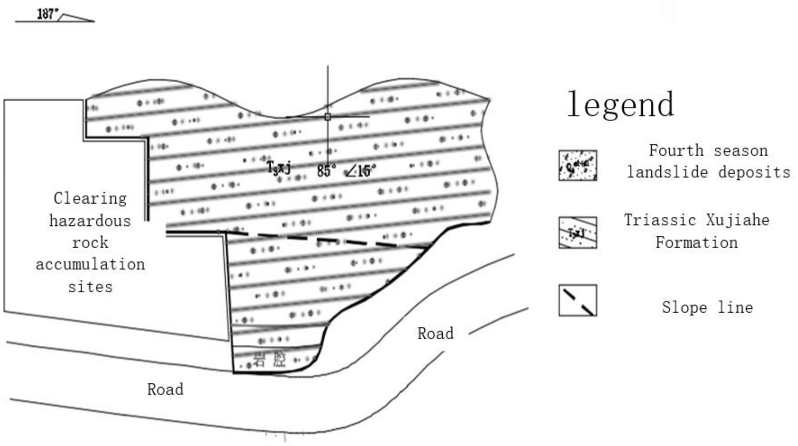


Figure 5 Design Plan for "Manual Hazard Removal

4.3 Mitigation Effect

The "Manual Hazard Clearance" scheme effectively mitigated the dangerous rock mass. Relevant authorities verified that the project met standards. The summary report of the geological disaster emergency hazard - removal project in Neijiang city indicates that threats to local residents have been basically eliminated, and the hazard point has been removed from the hazard list, confirming the mitigation effect.

5. Conclusions

1) This study successfully identified the location and scope of the dangerous rock collapse through a combined approach of remote - sensing analysis and on - site investigation, ensuring data accuracy and reliability. This method enhanced research efficiency, overcame shortcomings of field surveys in complex terrain, and enabled detailed analysis of individual dangerous rock masses.

2) The dangerous rock mass mainly consists of grey thick - to - blocky fine - grained sandstone from the Middle Jurassic Shaximiao Formation, with a hard lithology. Two sets of steep - dipping "X" joints were identified: Joint ① has a strike of 15° and dip of 88°, and is closed; Joint ② has a strike of 280° and dip of 87°, and is slightly open. Two tension joints, L1 and L2, parallel to Joint ②, were also identified.

3) The dangerous rock mass is relatively stable under natural conditions but unstable under heavy rain conditions, with storms being the main threat to its stability.

4) Two mitigation schemes, "Manual Hazard Clearance" and "Directional Blasting Hazard Clearance," were proposed. After considering mitigation effects, economic costs, and implementation difficulties, the "Manual Hazard Clearance" scheme was chosen. Subsequent monitoring confirmed the success of the mitigation project, with measures achieving the expected results.

Data sharing agreement

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, author-ship, and publication of this article.

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