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Rockfall Risk Assessment and Open-cut Tunnel Safety Evaluation at Railway Tunnel Portal Based on 3D Kinematic Simulation

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Abstract: ***To assess the rockfall risk at railway tunnel portals, this study proposes an integrated risk assessment methodology combining three-dimensional kinematic simulation and structural safety analysis. Taking a railway tunnel portal project as a case study, field investigations, UAV oblique photogrammetry, and laboratory-field tests were conducted to obtain rockfall distribution and geological data. A 3D reality-based model was established to characterize rock mass features. Three-dimensional kinematic simulations using Rockfall Hunter software were performed on representative rockfalls to analyze post-failure trajectories and impact energy on the Open-cut Tunnel structure. The structural safety of the Open-cut Tunnel was evaluated through finite element analysis. The results demonstrate that Rockfall W5 at Tunnel Portal I exhibits high collapse risk with maximum impact energy reaching 335.61 kJ, potentially causing direct effects on the Open-cut Tunnel structure. However, under current reinforcement conditions, the Open-cut Tunnel structure effectively resists impact loads, meeting structural safety requirements. Comprehensive analysis suggests prioritized risk control measures at Tunnel Portal I, where enhanced monitoring and protective measures are crucial for ensuring railway operational safety.***

Keywords: Rockfall, Oblique Photogrammetry, 3D Kinematic Simulation, Risk Assessment, Open-cut Tunnel Structure**.**

1. Introduction

With the rapid development of China's high-speed railway network, an increasing number of lines traverse mountainous regions, where tunnels and bridges now constitute a significantly higher proportion of infrastructure. Constrained by route alignment and topographic conditions, most tunnel portal sections feature steep side slopes and overhangs. These rock masses, affected by tectonic movements and weathering processes, exhibit complex geological characteristics. Under extreme weather events such as heavy rainfall or seismic activities, these slopes are prone to geological hazards including unstable rock masses, rockfalls, and collapses [1]. Rockfall hazards, characterized by stochastic trajectories, sudden occurrence, and multi-factor causation, pose significant threats to railway operational safety [2]. Typical case studies demonstrate catastrophic consequences: In November 2007, a massive rock collapse at the Gaoyangzhai Tunnel portal on the Yichang-Wanzhou Railway disrupted National Highway 318 and caused 35 casualties. Another incident in June 2022 involving sudden rockfall intrusion on the Guiyang-Guangzhou High-speed Railway resulted in 1 fatality and 8 injuries [3]. There is an urgent need to establish scientific evaluation and prevention systems for rockfall hazards during railway tunnel construction and operation.

Scholars worldwide have conducted research on rockfall hazards at tunnel portals. Gong et al. [4] developed a probabilistic risk assessment system by transforming subjective qualitative evaluations into objective quantitative analyses through hazard process decomposition and risk level classification. Ye et al. [5-6] proposed a hazard classification methodology, investigating rockfall kinematics through field experiments and comparing various impact force calculation methods. Cao et al. [7-10] employed airborne LiDAR and 3D oblique photogrammetry to identify failure mechanisms and spatial distribution patterns, while numerical simulations revealed 3D kinematic characteristics under different failure modes. Zhong et al. [11] established rockfall instability models using ROCFALL software, systematically analyzing trajectory parameters and impact energy. Finite element analysis of Open-cut Tunnel lining's impact resistance led to proposed comprehensive protection measures. Current research primarily focuses on rockfall stability assessment, with limited studies incorporating 3D kinematic characteristics for systematic risk analysis. Few studies address residual risk assessment post-mitigation. Nevertheless, comprehensive evaluations integrating 3D rockfall kinematics with existing infrastructure vulnerability remain insufficient.

This study focuses on a railway Tunnel portal project, employing integrated investigation methods combining UAV oblique photogrammetry and manual surveys to acquire rockfall data. A 3D reality-based model was constructed with statistical analysis to characterize rockfall dimensions, spatial distribution, and joint fissure patterns at the tunnel portal. Three-dimensional kinematic simulations were performed on representative rockfalls to assess potential risks and railway impacts. Concurrently, structural safety evaluation of existing Open-cut Tunnel under rockfall impacts was conducted. Ultimately, protective measures were proposed, providing theoretical and technical references for similar engineering projects.

2. Project Overview

The study area is situated in a bridge-tunnel transition section between Railway Tunnel Portal I and II, located within a low mountain-hill landform region. The terrain generally exhibits a concave profile with elevated ends and a depressed central quarry area. This benched excavation zone displays five to six distinct levels (levels II-VI), where steep cliff slopes adjacent to the bridge structure show face gradients of 70°-90°. Each bench has a vertical height of approximately 10 m, resulting in a total slope height of 70-80 m. At Tunnel Portal I, extensive exposed slopes formed by quarry excavation demonstrate near-vertical gradients (approaching 90°), with weathered bedrock surfaces hosting numerous rockfalls and falling stones. The railway alignment follows a northwest-southeast orientation through vegetated hill slopes and intermontane valleys, as shown in Figure 1.

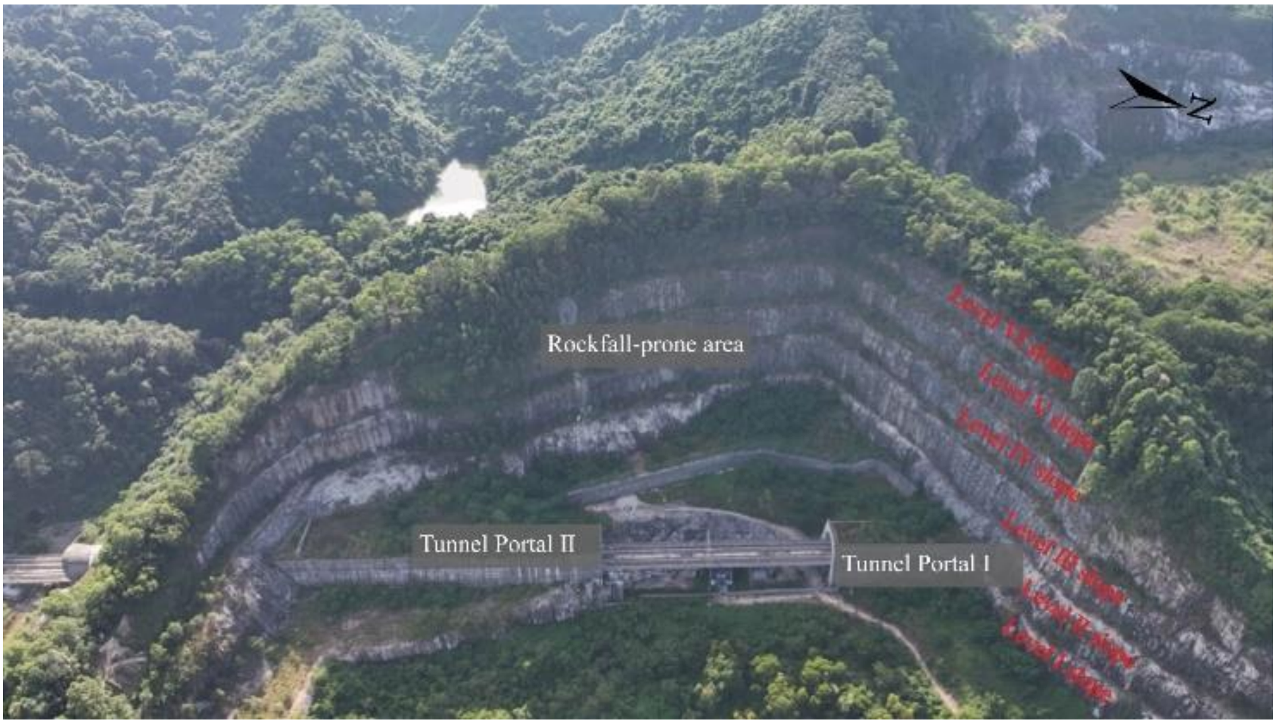


Figure 1: Topographic and Geomorphic Map of the Study Area

Based on regional geological data and field investigations, the engineering area is predominantly composed of Yanshanian Period granite (γ_5) with bluish-gray coloration and massive structure. The rock mass integrity ranges from moderately fractured to relatively intact, exhibiting well-developed joint systems and high lithological strength. Weathering profiles show complete decomposition layer (2-6 m thick) and strong weathering zone (3-4 m thick). Weakly weathered granite dominates the steep slopes above tunnel exits and along the railway's right side, characterized by intensive joint networks and fractured rock masses. Principal joint orientations are N42°E/80°SE and S31°E/15°NW, displaying tensile characteristics with apertures of 1-2 mm. Joint density reaches 2-5 fractures/m, predominantly lacking infill materials. Surface water systems consist primarily of valley-concentrated runoff, showing strong rainfall dependency. Ephemeral streams exhibit reduced flow or desiccation during dry seasons, while wet seasons trigger substantial runoff intensification. Groundwater systems include clastic rock pore-fissure water and carbonate karst water, predominantly recharged by lateral flow from surrounding mountains. Through pore networks and karst conduits, groundwater discharges to lower elevations with topography-controlled dynamics, demonstrating significant seasonal discharge variations.

3. Rockfall Investigation Methodology

This study implemented an integrated investigation approach combining manual field surveys and UAV obliquephotogrammetry to systematically characterize rockfall distribution patterns. High-resolution aerial imagery acquired by drones enabled the construction of a 3D reality-based model, facilitating identification and statistical analysis of rockfalls potentially affecting railway safety.

3.1 Manual Survey

Manual surveys were conducted through mountain climbing and on-site reconnaissance, with emphasis on documenting rockfall locations, morphological characteristics, geometric parameters, lithology, weathering grades, and structural features. Simultaneously, detailed descriptions were recorded regarding micro-topographic environments, vegetation types/coverage ratios, and joint network orientations / development characteristics surrounding rockfalls. Field observations revealed rock spalling phenomena at the Level IV slope of Tunnel Portal I, where weakly weathered rock masses produced detritus blocks measuring 10-30 cm in diameter. These spalling zones correspond to well-developed joint networks, with overhanging rock sections exhibiting imminent collapse risks (Figure 2). At the bridge-tunnel junction between Portals I and II, differential weathering at the Level V-VI slope interface triggered large-scale rock disintegration. Dislodged blocks traveled downslope, accumulating 25 m beyond the railway alignment within a 40 m² collapse zone. Detailed characteristics of railway-threatening rockfalls are presented in Table 1 and Figure 3.

Table 1: Summary of Rockfalls

No	Code	Volume (m^3)	Size Classification	Height Classification	Collapse Type	Collapse Direction (°)
1	W1	0.8	Small rockfall	High-level Rockfall	Drop-type collapse	23
2	W2	0.7	Small rockfall	Mid-level Rockfall	Drop-type collapse	58.7
3	W3	0.4	Small rockfall	Mid-level Rockfall	Drop-type collapse	76
4	W4	1.3	Small rockfall	High-level Rockfall	Drop-type collapse	135
5	W5	0.5	Small rockfall	Mid-level Rockfall	Drop-type collapse	130

Figure 2: Photographic Documentation of Rockfall Hazard at Level IV Slope

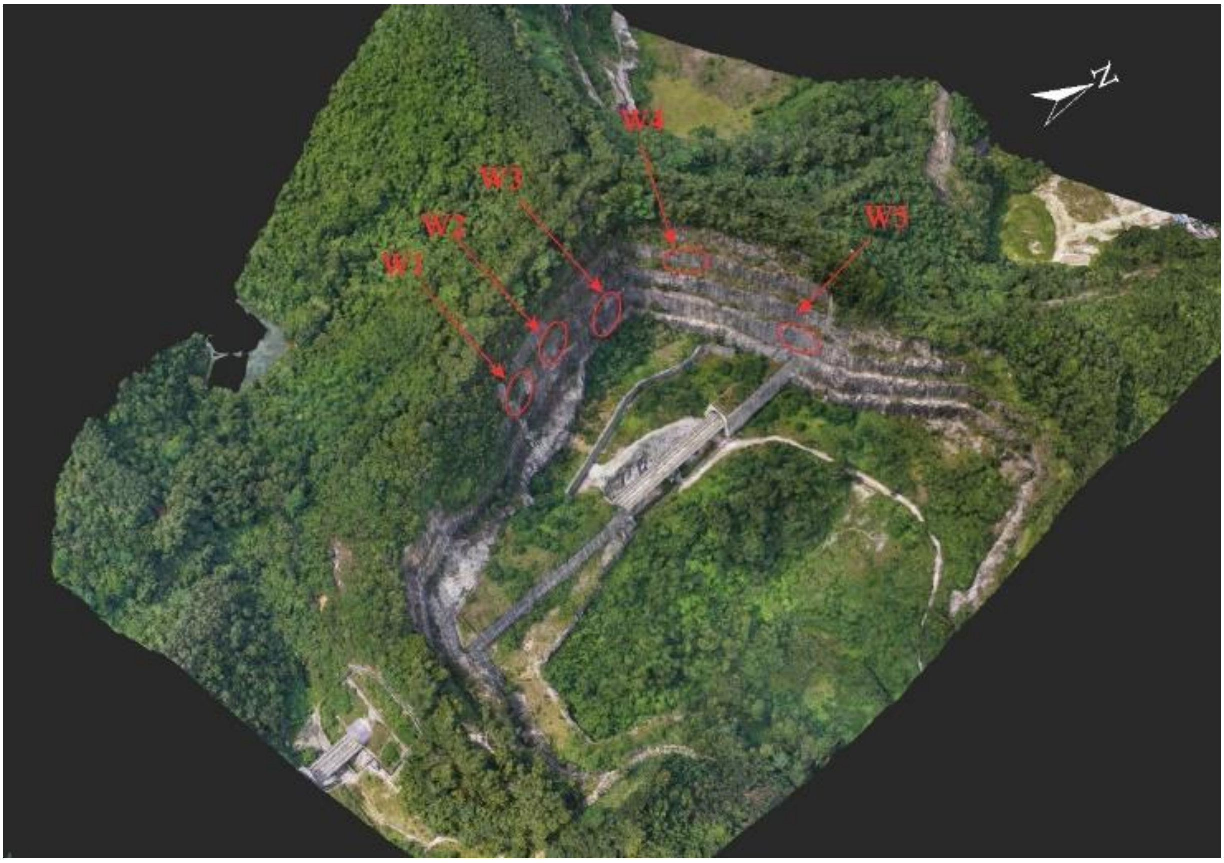


Figure 3: 3D Digital Model of the Study Area

3.2 UAV Oblique Photogrammetry

This investigation implemented UAV oblique photogrammetry to achieve efficient and precise terrain data acquisition in the study area. The methodology employs multi-camera arrays on a single UAV platform to synchronously capture multi-angle imagery, enabling rapid acquisition of high-resolution, multi-perspective geospatial data. The derived 3D oblique model accurately reconstructs terrain morphology, visually demonstrating topographic undulations, geological contexts, and rockfall distribution patterns. This advanced technique has become essential for geological hazard investigation and risk assessment in steep terrains. The survey utilized DJI Phantom 4 RTK UAV platform configured with 200 m AGL flight altitude, 80% longitudinal overlap, and 70% lateral overlap. A total of 1,247 raw images with 2 cm GSD were acquired, from which a georeferenced 3D digital model (Figure 3) was generated, providing reliable data foundation for subsequent rockfall kinematic simulations.

4. Rockfall Risk Assessment

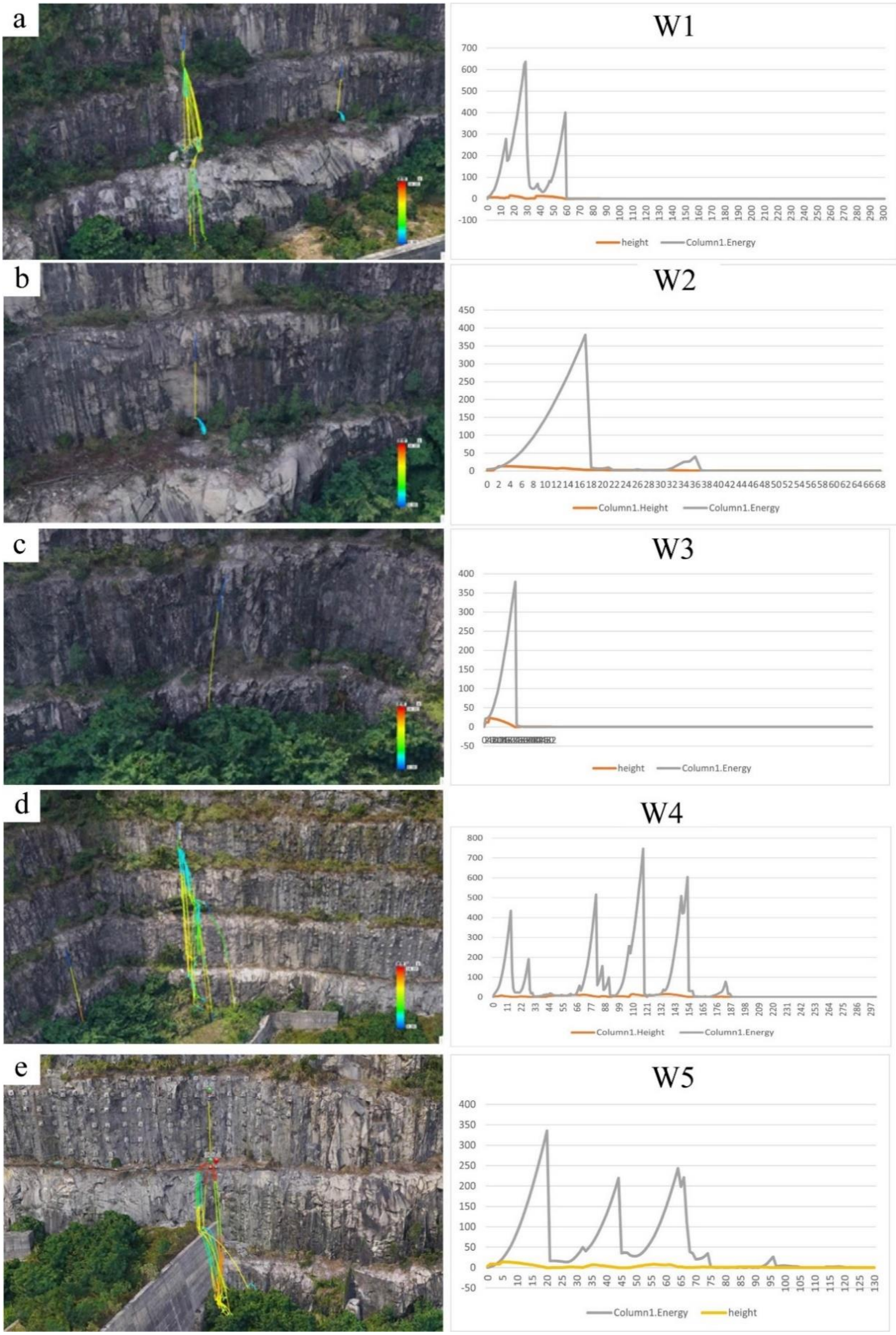


Figure 4: 3D Kinematic Simulation Analysis

4.1 Failure Mechanism Analysis

The engineered slopes with 70°-90° gradients created by excavation activities provide geomechanical conditions conducive to rockfall formation. The combination of well-developed joint networks and differential weathering in granite slopes has induced structural plane-controlled block formation through excavation activities. These rockfall blocks (1-5 m in diameter) with rhombic, cubic, or irregular geometries are distributed along cliff faces. Extreme meteorological events (e.g., torrential rainfall, typhoons) may trigger downslope block detachment, posing threats to toe structures and railway operations.

4.2 3D Kinematic Simulation

This study implemented a particle-based method using the in-house developed Rockfall Hunter software for numerical simulation of rockfall kinematics. The 3D digital model integrated with field mapping and laboratory-field test data enabled slope-specific parameterization of normal/tangential restitution coefficients and friction coefficients. Monte Carlo simulations with 95% confidence level were conducted (20 iterations per rockfall), incorporating geometric configurations and mass parameters. Launch angles (±20° from slope dip direction, 2° increments) and initial conditions (0.5 m/s horizontal/vertical velocities at 0.5 m elevation) were defined, with motion termination at 0.1 m/s velocity threshold. Five hazardous rockfalls (W1-W5) identified through manual surveys were selected for representative simulation. Bare cliff surface parameters yielded key kinematic indicators: maximum vertical drop, horizontal runout, bounce height, and impact energy at tunnel portals. Trajectory plots, bounce height distributions, and impact energy patterns are shown in Figure 4, with 3D kinematic parameters detailed in Table 2. Simulation results reveal dominant motion modes: collision-rebound and free-fall mechanisms, with occasional rolling/sliding on gentle terrains. Table 2 demonstrates that rockfalls W1-W4 exhibit trajectories outside railway clearance limits, posing negligible operational risks. Conversely, Rockfall W5 demonstrates direct impact trajectory on the Open-cut Tunnel roof at Portal I, with maximum impact energy reaching 335.61 kJ, necessitating prioritized mitigation measures.

Table 2: 3D Kinematic Parameters

Code	Volume (m^3)	Maximum Horizontal Displacement(m)	Maximum Bounce Height(m)	Impact Energy(kJ)	Distance from Rockfall Landing Point to Railway Alignment
W1	0.8	17.17	15.12	636.68	>50m
W2	0.7	14.20	13.26	381.25	>55m
W3	0.4	18.74	23.11	379.25	>60m
W4	1.3	14.51	16.37	739.06	>35m
W5	0.5	15.78	14.47	335.61	Fell onto the top of the open-cut tunnel

5. Structural Safety Assessment of Open-cut Tunnel under Rockfall Impact

Simulation results demonstrate that Rockfall W5's trajectory will directly impact the roof of the Open-cut Tunnel at Portal I. With an estimated volume of 0.5m^3 and maximum simulated impact energy of 335.61 kJ, this rockfall poses potential hazards to the tunnel structure. A targeted safety evaluation was conducted incorporating structural impact resistance analysis, leading to formulated protective measures to ensure operational safety.

5.1 Impact Load Intensity Calculation

According to the Technical Guidelines for the Prevention and Control of Rockfall Hazards in Railway Engineering (Q/CR 9578-2024), the impact load intensity is generally calculated using the following formula.

$$q = \frac{P_{max}}{\pi(R+h_m \cdot tan\varepsilon)^2}$$

Where q is Impact load intensity (kPa), P_{max} is Maximum impact force of the rockfall (kN), R is Equivalent spherical radius of the rockfall (m), taken as 0.493 m, ε is Impact diffusion angle (°), generally ranges from 35° to 40°, taken as 37°, h_m is Average thickness of the cushioning layer (m), taken as 1.5 m.

The impact force of falling rocks is typically determined in accordance with the methodology outlined in the Railway Engineering Design Technical Manual – Tunnel (Revised Edition).

$$P = \frac{Qv_0}{gT}$$

Where P is Impact force of the rockfall (kN), Q is Weight of the rockfall (kN), v_0 is Velocity at the moment of impact (m/s2), T is Duration of impact (s). $Q = \gamma \cdot V = 25\text{kN}/m^3 \times 0.5m^3 = 12.5kN$, The impact energy of the rockfall at location W5 is 335.61 kJ. Based on the kinetic energy equation $E = \frac{1}{2}mv^2$ the initial impact velocity is calculated to be: $v_0 = 23.17\text{m}/s^2$.

The impact duration is approximately calculated as the time it takes for the compressive shock wave to propagate through the buffer backfill soil, using the following formula:

$$T = \frac{2h}{c}$$

$$c = \sqrt{\frac{(1-\mu)}{(1+\mu)(1-2\mu)} \cdot \frac{E}{\rho}}$$

Where h is Thickness of cushion backfill (m), taken as 1.0m, μ is Poisson's ratio of the backfill material, taken as 0.38,E is Elastic modulus of the backfill material (kPa), taken as 32000 kPa, ρ is Density of the backfill material (*kg/m^3*), taken as 1730 kg/m^3.

Based on the above parameters and the relevant calculation formula, the impact duration is determined to be: T= 0.34s, Accordingly, the impact force is calculated as: P = 86.96kN. Thus, the impact load intensity is obtained as: q = 10.52kPa.

5.2 Computational Modeling of Open-cut Tunnel

The finite element model was developed using Midas GTS NX, with impact load q applied to left-side backfill soil (Figure 5). Load combinations were formulated as:

- Ultimate limit state (ULS): $S_d = 1.2G + q$,
- Quasi-permanent state (QLS): $S_d = G + q$.

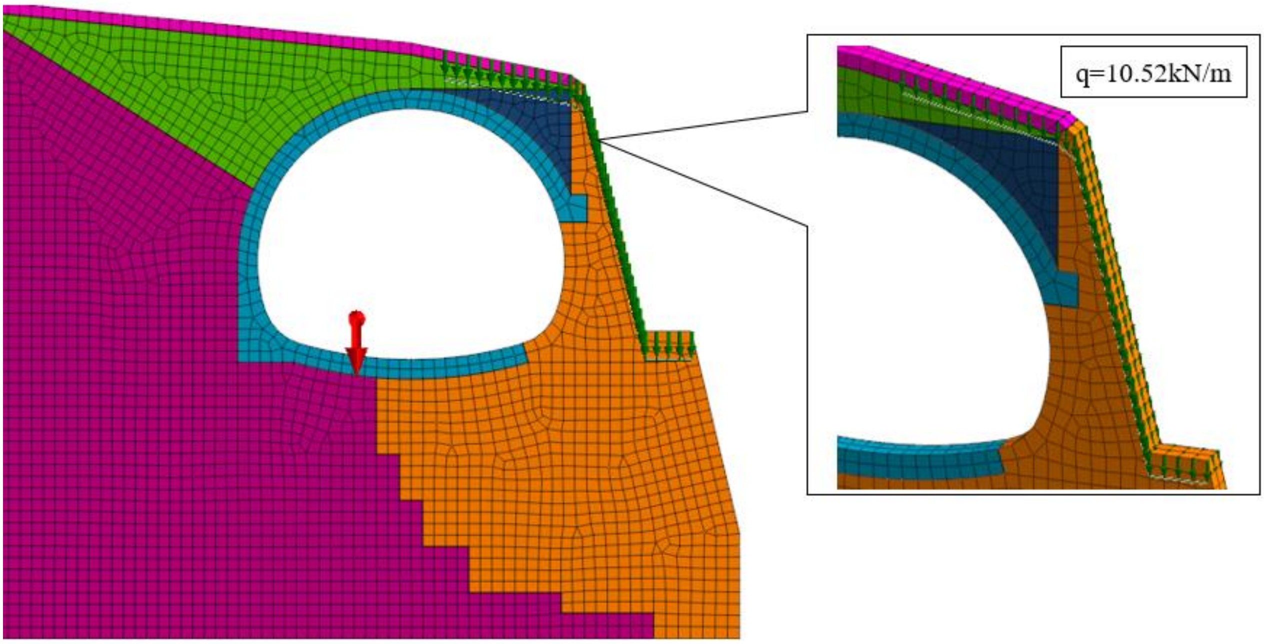
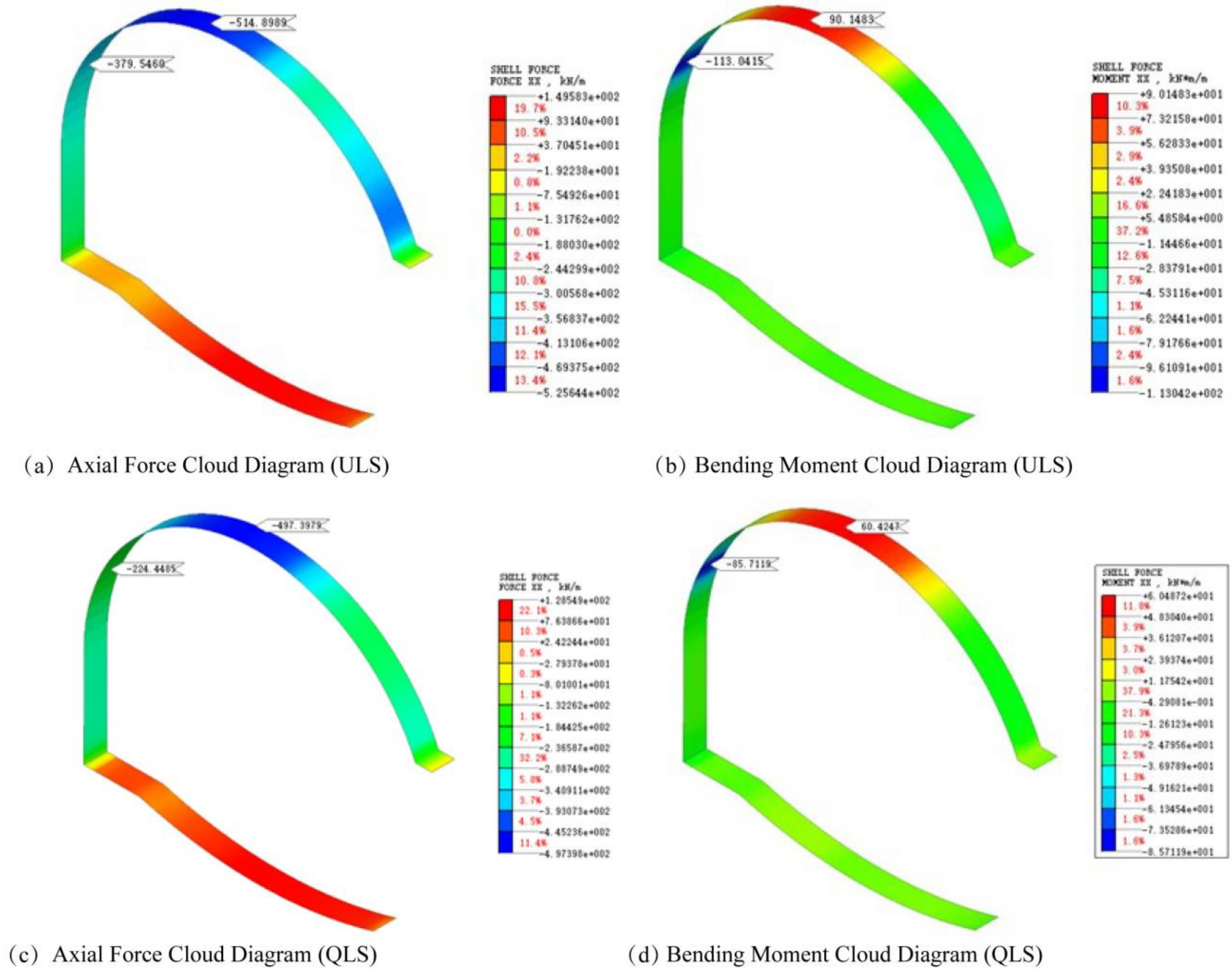


Figure 5: Schematic Diagram of Impact Load Application

5.3 Computational Results

The 3D numerical model was reduced to 2D shell elements with 0.85 m lining thickness for structural analysis. Numerical simulations were performed to determine internal forces under ultimate (ULS) and quasi-permanent (QLS) load combinations considering rockfall impact loads. Results indicate maximum internal forces per unit length under ULS condition: Axial force: -514.90 kN, Bending moment: -113.04 kN·m. Under QLS condition, peak values are: Axial force: -497.40 kN, Bending moment: -85.71 kN·m.



(a) Axial Force Cloud Diagram (ULS)

(b) Bending Moment Cloud Diagram (ULS)

(c) Axial Force Cloud Diagram (QLS)

(d) Bending Moment Cloud Diagram (QLS)

Figure 6: Structural Force Distribution Diagram

5.4 Structural Verification

Calculation based on the flexural capacity formula for rectangular sections in the Code for Design of Concrete Structures shows the required reinforcement area under current impact load is $A_s = A'_s \geq 725.51\text{mm}^2$. The existing reinforcement area of the Open-cut Tunnel (As=As′=3799.4 mm^2) meets reinforcement requirements.

Crack width verification using:

$$W_{fmax} = \alpha_{cr}\varphi\frac{\sigma_s}{E_s}\left(1.9c_s + 0.08\frac{d}{\rho_{te}}\right)$$

indicates negligible crack width (effectively 0 mm) under W5 impact load, demonstrating no structural effect.

Therefore, the rockfall at W5 poses no threat to the structural safety of the Open-cut Tunnel.

6. Conclusions

1) Through the integration of UAV oblique photogrammetry and manual field surveys, this study developed a 3D reality-based model of the tunnel portal area. Quantitative analysis revealed significant rockfall accumulation at Tunnel Portal I, particularly on steep slopes (70°-90°), demonstrating detachment risks under extreme weather or seismic conditions.

2) Numerical simulations using Rockfall Hunter software identified distinct kinematic patterns: Rockfalls W1-W4 remain outside railway clearance limits, while Rockfall W5 exhibits direct impact trajectory on the Open-cut Tunnel roof at Portal I with maximum impact energy of 335.61 kJ, posing operational risks.

3) Structural analysis confirmed the Open-cut Tunnel's capacity to withstand Rockfall W5 impacts. Existing reinforcement (3,799.4 mm^2/m) exceeds required levels (725.51 mm^2/m), with crack width calculations indicating no structural compromise.

4) Mitigation strategies include: (1) Enhanced monitoring systems for high-risk zones; (2) Protective measures for Rockfall W5; (3) Regular slope maintenance to ensure long-term railway safety.

Acknowledgement

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References

[1] Wang, Y., & Yang, G. (2010). Risk assessment of rockfalls in tunnel portal sections. Modern Tunnelling Technology, 47(6), 33-39.

[2] Hu, H. (2005). Study on collapse and rockfall. Journal of Railway Engineering, (S1), 387-391.

[3] Dang, D. (2023). Risk management of rockfall hazards at mountain railway tunnel portals [Doctoral dissertation, Lanzhou Jiaotong University].

[4] Gong, S., Ye, S., & Yang, W. (2014). Probabilistic risk assessment methodology for rockfall hazards. Journal of Catastrophology, 29(4), 215-219.

[5] Ye, S., & Chen, H. (2010). Hazard classification method for rockfall disasters on tunnel portal slopes. *China Railway Science*, 31(5), 59-65.

[6] Deng, Y. (2022). *Key technologies for rockfall prevention and control in complex mountain tunnel portals* [Master's thesis, Southwest Jiaotong University].

[7] Cao, H. (2024). Risk assessment of rockfalls at railway tunnel portals under high vegetation coverage. *Railway Standard Design*, 68(5), 122-129.

[8] Li, H., Wang, Y., & Liu, G. (2023). Rockfall risk assessment based on fuzzy logic and 3D kinematic simulation. *Subgrade Engineering*, (5), 195-200.

[9] Li, G. (in press). Comprehensive investigation and analytical evaluation of rockfalls at a railway tunnel portal. *Railway Standard Design*. Advance online publication. Retrieved May 8, 2025, from [URL]

[10] Li, G. (2022). Analysis and protective design of rockfalls at shallow-buried high-speed railway tunnel entrances. *Railway Investigation*, 48(6), 83-88.

[11] Zhong, C., Zhang, L., & Zhou, L. (2022). Evaluation methods and engineering countermeasures for rockfall disasters at high-speed railway tunnel portals. *High-Speed Railway Technology*, 13(6), 84-91.