

Geological and Geotechnical Assessment Report along Cut Slope in Connection with Barkhera– Budni 3rd Line Project Bhopal

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ABSTRACT

The study focuses on the assessment and mitigation of rockfall and landslide hazards along an existing railway corridor in Budhni Town, Sehore District, Madhya Pradesh, India. The project area lies between chainages 9+000 km and 14+580 km along a 5.8 km long railway section Barkhera –Budni 3rd Line Project Bhopal which is located within the central part of India. The region is characterized by rugged terrain and adverse geological conditions, where repeated incidents of boulder falls and rainfall-induced slope failures pose a significant threat to railway operations and safety.

Detailed engineering geological mapping was carried out along the track alignment to characterize the slope mass, lithology, structural discontinuities, and weathering conditions. The rock mass predominantly comprises highly weathered siltstone and sandstone, with large embedded and hanging boulders present on the upper slopes. Field observations indicate that intense monsoonal rainfall significantly contributes to slope instability by reducing shear strength and triggering landslides and rockfall events.

Kinematic analysis was performed using stereographic projection techniques to identify potential modes of structurally controlled failure, including planar, wedge, and toppling mechanisms. In addition, rockfall analysis was conducted using Rocscience software to simulate boulder trajectories, bounce heights, runout distances, and impact energies along the railway corridor. The results indicate that several slope sections are kinematically unstable and capable of generating rockfalls that can reach the railway track with considerable kinetic energy.

Based on the integrated geological, kinematic, and numerical analyses, appropriate upper-slope stabilization and rockfall mitigation measures were proposed to reduce hazard levels and improve the long-term safety of the railway infrastructure. The study highlights the importance of combining field-based geological assessment with analytical and numerical tools for effective slope protection design in rainfall-prone regions.

Keywords: Rockfall analysis; Slope stability; Kinematic assessment; Railway slope protection; Engineering geology; Landslide mitigation

INTRODUCTION

Rockfall and rainfall-induced landslide hazards pose a significant threat to railway infrastructure in hilly and geologically complex terrains. In central India, several railway corridors traverse steep slopes composed of highly weathered rock masses, where intense monsoonal rainfall frequently triggers slope instability and boulder falls. Such events disrupt railway operations and raise serious safety concerns, highlighting the need for systematic hazard assessment and mitigation.

This study focuses on a 5.8 km long section of the Barkhera–Budhni 3rd Line Railway Project near Budhni Town, Sehore District, Madhya Pradesh, India. Detailed investigations were carried out along the railway alignment between chainages 9+000 km and 14+580 km, a stretch that has experienced repeated incidents of rockfall and slope failure. The area is characterized by rugged topography and slopes comprising predominantly highly weathered siltstone and sandstone with embedded and hanging boulders.

Engineering geological mapping was undertaken to characterize lithology, slope geometry, discontinuity patterns, and weathering conditions. Kinematic analyses using stereographic projection techniques were performed to identify potential structurally controlled failure modes, including planar, wedge, and toppling failures. Rockfall simulations were carried out using Rocscience software to evaluate boulder trajectories, runout distances, bounce heights, and impact energies.

Study Area

The study area is located near Budhni Town in Sehore District, Madhya Pradesh, India, and forms part of the Barkhera–Budhni 3rd Line Railway Project. The investigated stretch extends between chainages 9+000 km and 14+580 km, covering a total length of approximately 5.8 km along the existing railway alignment.

The region is characterized by rugged physiography with steep natural and cut slopes, influenced by a tropical monsoonal climate. Intense seasonal rainfall significantly affects slope stability, often triggering surface erosion, landslides, and rockfall events along the railway corridor.

Geologically, the area is dominated by sedimentary formations comprising siltstone and sandstone, which are generally highly weathered and fractured. The degree of weathering and the presence of unfavorable discontinuity orientations contribute to slope instability, particularly on upper slopes where detached and hanging boulders are commonly observed. As per IS 1893 (Part 1): 2025, the project area falls under Seismic Zone III.

The location and extent of the study area are shown in Figure 1.

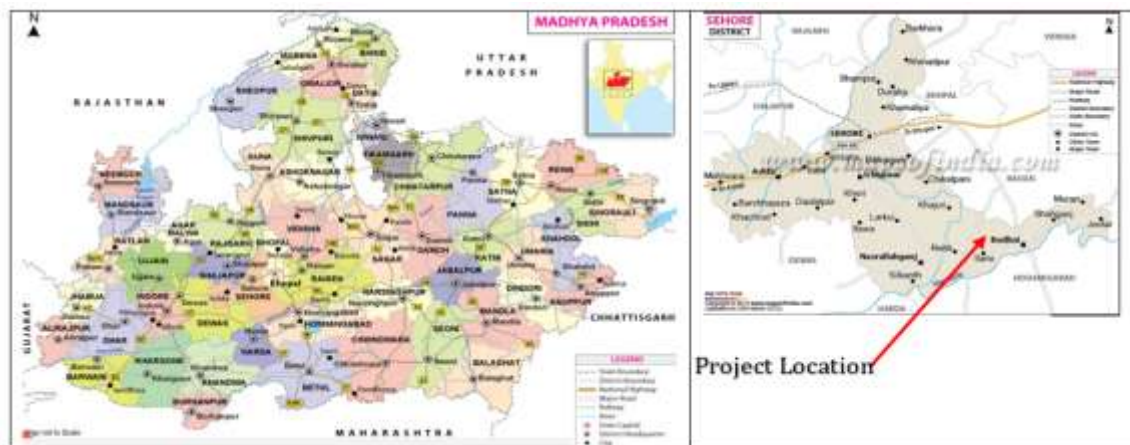


Figure 1: Project Location (Source Map of India)

Problem Description

The project stretch from Ch. 8+900 km to Ch. 14+700 km is characterized by complex geological and geomorphological conditions, predominantly comprising highly weathered shale and siltstone formations overlain by thick slope wash and overburden material. The overburden consists of sandy–silty soil mixed with cobbles and large boulders ranging in size from 0.2 m to 18 m, many of which are loose, embedded, or hanging on steep slopes. The rock mass is moderate to highly weathered, jointed, foliated, and medium strong, with low dip angles (5° – 10°) trending between 120° and 150° , which may adversely influence slope stability depending on slope orientation.

Several instability zones have been identified during surface geological mapping, including five major slides (Slide-1 to Slide-5) occurring at different chainages, particularly near bridge abutments, tunnel portals, and cut slopes formed after benching. Failure slopes range between 40° and 50° , and the failed mass typically comprises boulders, cobbles, and sandy–silty matrix, indicating debris-type slope failures. Certain stretches show complete absence of rock outcrops, with the terrain entirely covered by loose slope wash and large boulders.

Critical zones are observed near Tunnel No. 2 (Midghat tunnel) and the proposed Tunnel No. 3, where unstable overburden, thinly foliated shale, subsidence-related failures, and large unstable boulders (up to 10×15 m) pose significant hazards. Seasonal nala activity and debris accumulation further increase the likelihood of rockfall and slope instability during monsoon periods. Although groundwater conditions are generally dry, the high degree of weathering, weak rock mass conditions, and presence of heavy infrastructure such as railway tracks, bridges, tunnels, and proposed cut-and-cover sections make this stretch highly vulnerable and require detailed slope stabilization and mitigation measures.



Figure 2: Slide from Ch.10+820 to Ch.10+960 Km with potential rockfall hazard.



Figure 3: Unstable zone at the top of slope between Ch. 12+850 km and Ch. 12+950 km.



Figure 4: Slide Near to Bridge No. 27



Figure 5: Unstable zone and Shale at Portal-2 of Tunnel No.2

Kinematic Analysis

Based on the kinematic analysis of the cut slopes, the potential for toppling, planar, and wedge failures was identified at selected chainages. At Ch. 10+700 km, the analysis indicates a possibility of toppling failure involving approximately 50% of joint set J4, planar failure along joint set R2 (random joint), and wedge failure formed by the intersection of joint sets J2 and R2 (random joint), as well as J3 and R1 (random joint). Similarly, at Ch. 14+300 km, toppling failure is anticipated along joint set R1 (random joint), while wedge failure may occur due to the intersection of joint sets J3 and J4. No significant planar failure was observed at this location. These results highlight structurally controlled instability and the need for appropriate slope stabilization measures at the identified chainages.

Table 1: Details of Joint Set for Ch. 10+700 Km

Set No.	Dip Amount (°)	Dip Direction (°)
J1/Foliation	06	139
J2	85	038
J3	81	295
J4	78	226
R1	77	145
R2	51	30

Table 2: Details of Joint Set for Ch. 14+300 Km

Set No.	Dip Amount (°)	Dip Direction (°)
J1/Foliation	10	250
J2	81	050
J3	80	100
J4	85	316
R1	85	220

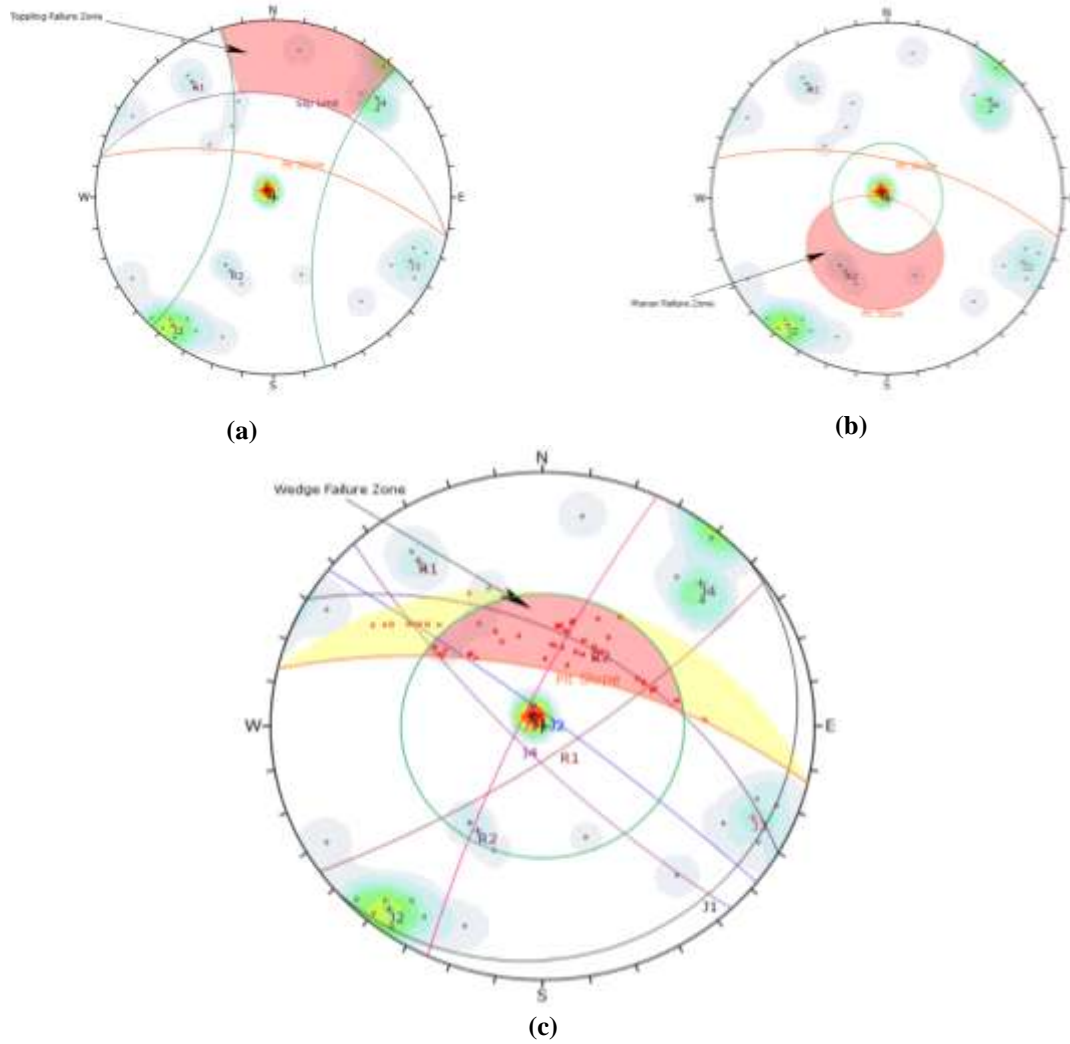


Figure 2: Stereographic projection for (a) Toppling Failure Zone; (b) Planar Failure Zone; (c) Wedge Failure Zone at Ch. 10+700 Km

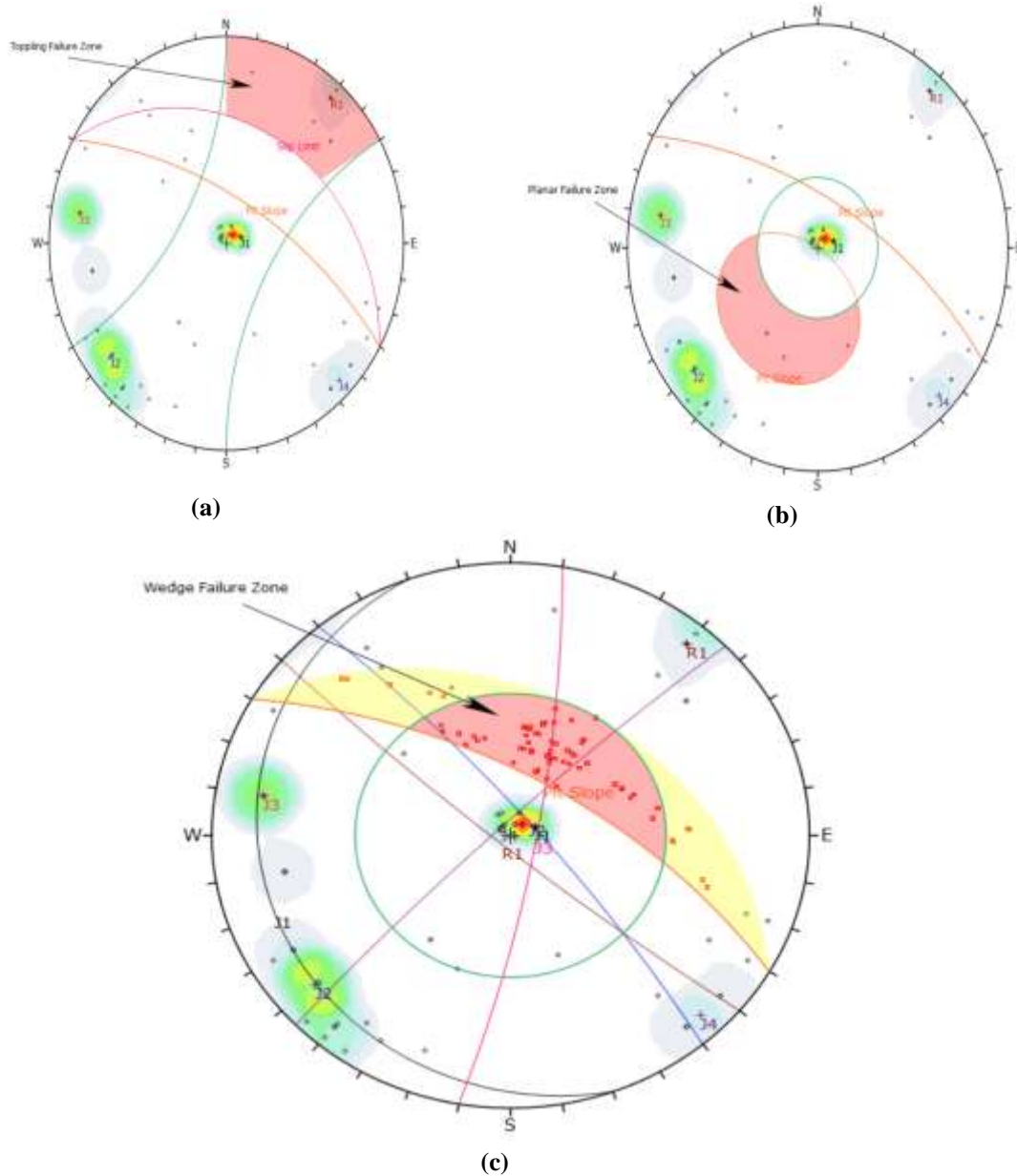


Figure 3: Stereographic projection for (a) Toppling Failure Zone; (b) Planar Failure Zone; (c) Wedge Failure Zone at Ch. 14+300 Km

Rockfall Analysis

A detailed rockfall hazard assessment was conducted to evaluate the risk to the railway track and to design appropriate mitigation measures. The critical design parameters for passive protection systems, such as rockfall barriers, are the maximum bounce height and impact energy of falling blocks. These parameters were determined through numerical simulation.

Rockfall modelling was carried out using RocFall 2D, developed by Rocscience Inc. The program applies rigid body analysis to simulate block trajectories, velocities, energies, and run-out distances. Surface parameters such as restitution coefficients, friction, and roughness were selected based on field observations and published data for similar geological conditions.

Two categories of rock blocks were considered: small rocks (1,000 kg) and large rocks (10,000 kg), both with a density of 2,700 kg/m³ and varying geometrical shapes. A total of 1,000 blocks were simulated from three critical release locations without any protective measures to assess the worst-case scenario.

Table 3: Summary of Rockfall Analysis

Envelope Data	Maximum	Mean
Envelope Bounce Height (m)	20.22	9.126
Envelope Total Kinetic Energy (kJ)	5041	1438
Envelope Translational Kinetic Energy (kJ)	4444	1413
Envelope Rotational Kinetic Energy (kJ)	618	166
Envelope Translational Kinetic Velocity (m/s)	35.53	27.62
Envelope Rotational Kinetic Velocity (rad/s)	41.16	30.6

The results indicated a maximum bounce height of 20.22 m and a maximum total kinetic energy of 5,041 kJ. The high translational energy component suggests a significant risk of impact on the railway track.

Based on the simulation outcomes, rockfall poses a considerable hazard in the study area. Therefore, installation of a high-tensile rockfall barrier system with a minimum energy absorption capacity of 5,000 kJ was recommended.

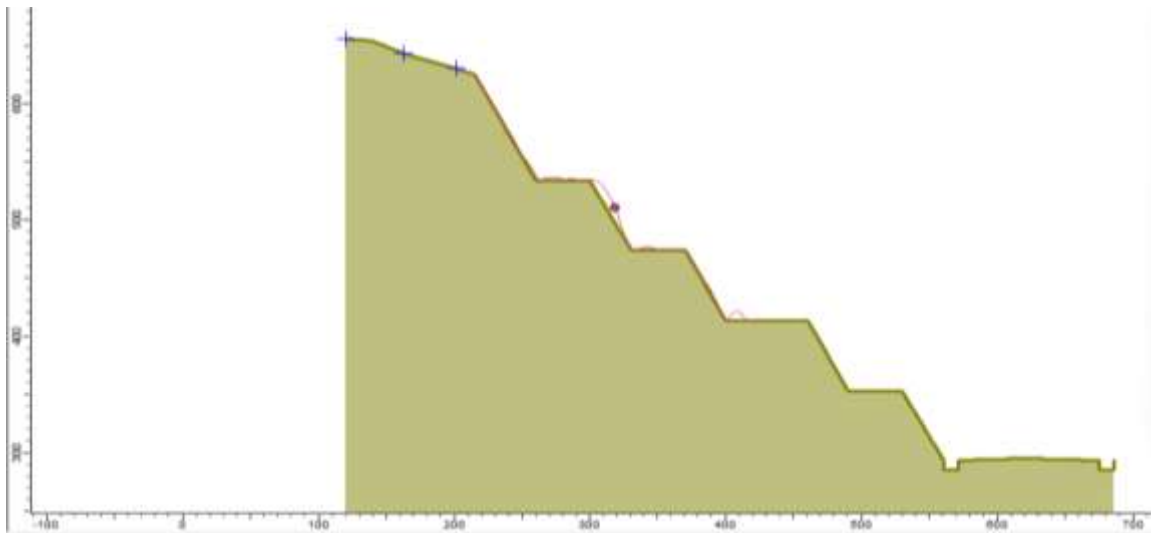


Figure 4: A simulation of a falling boulder

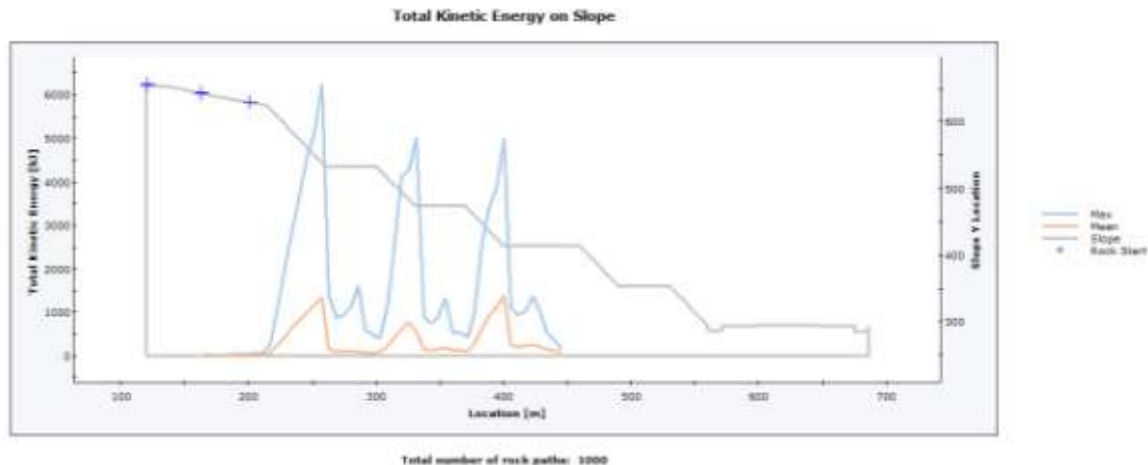


Figure 5: Total Kinetic Energy on Slope

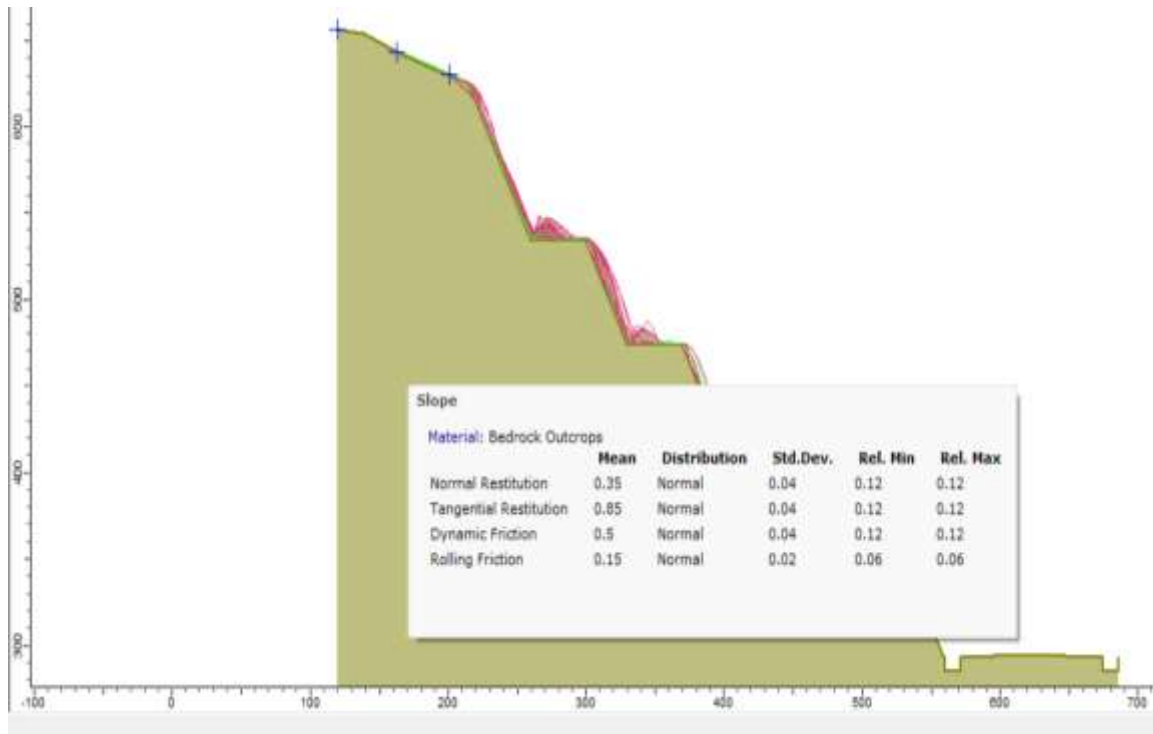


Figure 6: Material Properties

Mitigation Measures

Based on detailed field investigations, structural mapping, and stability assessments, mitigation measures were proposed to address instability of cut slopes and rockfall/debris flow hazards along the railway alignment. The stabilization strategy was designed considering observed failure mechanisms, hydrogeological conditions, and operational safety requirements.

- **Cut Slope Stabilization:** The cut slopes were found to be affected by weathering, discontinuity-controlled failures, and water infiltration during monsoon periods. To improve surface stability and prevent raveling, a 100 mm thick shotcrete layer reinforced with welded wire mesh was applied over vulnerable slope faces. In highly fractured zones, heavier mesh was adopted.

For structurally controlled failures such as planar, wedge, and toppling modes, fully grouted 25 mm diameter, 6 m long self-drilling anchors were installed at 1.2–1.5 m spacing. These anchors enhanced block interlocking and increased shear resistance along discontinuities.

To control the adverse effects of groundwater, sub-horizontal drainage holes fitted with perforated PVC pipes were provided in a staggered arrangement. This reduced pore water pressure within the slope mass. Additionally, a reinforced concrete toe wall was constructed at the slope base to provide passive resistance and protect the railway track from minor rockfall and debris accumulation.

- **Rockfall and Debris Flow Mitigation:** Field observations indicated the presence of large unstable boulders on upper slopes, particularly in zones underlain by weathered shale and siltstone with clay interlayers. During periods of intense rainfall, reduction in shear strength and toe erosion increased the likelihood of rockfall. Large unstable blocks were therefore removed through controlled blasting to eliminate potential detachment sources.

Rockfall trajectory analysis identified critical sections where falling blocks could reach the railway corridor. Flexible rockfall barriers were installed at these locations to absorb and dissipate impact energy, thereby ensuring operational safety.

Several drainage channels within the study area contained loose debris deposits. During monsoon events, this material was prone to mobilization as debris flow. To mitigate this hazard, debris flow barriers were installed across selected channels, oriented perpendicular to the flow direction. Gully net systems were used for narrow spans, while post-supported high-strength steel mesh systems were adopted for wider channels to resist dynamic debris loading.

CONCLUSIONS

- A detailed case study was carried out along the 5.8 km Barkhera–Budhni railway stretch near Budhni, Madhya Pradesh.
- Geological mapping revealed highly weathered shale–siltstone slopes with large unstable and hanging boulders.
- Kinematic analysis confirmed planar, wedge, and toppling failure potential at critical chainages.
- Rockfall modelling predicted bounce heights up to 20.22 m and peak impact energy up to 5,041 kJ, indicating high risk to the track.
- High-energy flexible rockfall barriers ($\geq 5,000$ kJ capacity) were recommended at critical sections based on simulation results.
- In debris-prone nalas, debris flow barriers were proposed to intercept and retain mobilized material during monsoon events.
- The case study demonstrates that integrated geological investigations combined with numerical modelling enable effective, site-specific mitigation design for railway infrastructure in rainfall-prone terrains. The installed mitigation measures are shown in Figures 11 and 12.



Figure 7: Installed Rockfall barrier at Tunnel Portal
(Photo Source: RVNL Report)



Figure 8: Cut Slope Stabilization

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