Research Article DOI: https://doi.org/10.64862/ajeg.2025.201.04 Open Access

Comprehensive Evaluation and Practical Stabilization of Roadside Rock-Cut Slopes along the Narayangadh–Mugling Highway Section

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Received: September 12, 2024, Accepted: June 15, 2025

Abstract: The Narayangadh–Mugling Highway corridor in Nepal is highly vulnerable to recurrent rock-cut slope failures—including rockslides, rockfalls, toppling, and debris flows—that pose significant risks to life, infrastructure, and transportation. Two representative high-risk slopes were investigated through geological mapping, discontinuity surveys, and slope geometry measurements. Laboratory testing determined rock strength parameters and discontinuity shear strength. Rock mass quality was evaluated using RMR_{basic} and Slope Mass Rating (SMR) systems. Kinematic analysis identified potential planar, wedge, and toppling failures, while numerical modeling with SLIDE 5.0 computed factors of safety (FoS) under existing and remedial conditions. Both slopes were found to be critically unstable under current conditions. Installation of rock anchors at −150° significantly improved stability, while slope re-profiling to 60° (1H:1.73V) further enhanced performance. The combined approach of re-profiling with anchoring was identified as the most economical solution. The study provides practical insights for designing targeted slope stabilization measures, offering guidance for reducing geohazard risks along this critical transportation corridor.

Keywords: ***Slope stability analysis, Rock anchors, Optimum rock-cut slope angle, Kinematic analysis, RMR_{basic}, SMR.***

Introduction

Slope failures are common along rock-cut slopes in mountainous road corridors, often causing fatalities, injuries, and economic losses (Ahmad and Joshi, 2010; Aleotti and Chowdhury, 1999). These failures may occur as rockslides, rockfalls, topples, debris flows, or combinations thereof (Brunsden et al., 1981; Gerrard, 1994; Owen, 1991; Regmi et al., 2013a, 2013b; Shroder and Bishop, 1998), and their prevention is critical for maintaining transportation infrastructure (Sharma et al., 2013).

Inappropriate excavation techniques, steep cut angles, and blasting-induced vibrations can reduce slope stability by enlarging pre-existing cracks and activating minor faults (Singh et al., 2013; Umrao et al., 2011). In the Himalayas, slope failures are often linked to lithological variability, unfavorable discontinuity orientations, weak overburden, and hydrological influences (Kainthola et al., 2015).

The 36 km Narayangadh–Mugling Highway corridor, a crucial link between the capital and the Terai plains carrying over 90% of consumer goods, industrial raw materials, and fuel (World Bank, 2025), traverses high mountains, rolling hills, and flat terrain. This corridor is highly susceptible to landslides, with frequent rockslides, topples, and debris flows (Khanal and Dahal, 2024), including notable events such as the burial of a police vehicle in 2017 (Onlinekhabar, 2017). Despite these recurrent hazards, existing studies provide limited guidance on site-specific mitigation strategies that integrate geological, geotechnical, and numerical stability analyses.

Rock mass classification systems such as RMR_{basic} (Bieniawski, 1973; Bieniawski, 1976; Bieniawski, 1989) and SMR (Romana, 1985; Romana, 1995) provide quantitative measures of rock quality, while kinematic analysis evaluates planar, wedge, and toppling failure potential based on slope–discontinuity relationships (Goodman, 1995; Goodman, 2000; Haswanto and Abd-Ghani, 2008). Numerical limit equilibrium modeling using SLIDE 5.0 (Rocscience, 2006) enables factors of safety (FoS) computations for complex surfaces, and mitigation measures such as rock anchors and slope re-profiling are commonly applied (Kliche, 1999).

In this study, these tools were applied to two representative high-risk slopes (RS-1 and RS-2) selected through systematic field assessment. Selection criteria included frequent past failures, representative geological and geotechnical conditions (weathered rock, critical discontinuities, weak overburden), proximity to essential road infrastructure, and accessibility for detailed monitoring. These slopes exemplify the failure mechanisms observed throughout the corridor. The study provides a comprehensive evaluation of slope stability, integrating field investigations, laboratory testing, rock mass classification, kinematic analysis, and numerical modeling to develop practical stabilization measures tailored to the corridor's challenging terrain.

Study area

The 36 km Narayangadh–Mugling Highway corridor lies in Chitwan District, central Nepal, spanning 84°25'00"–84°35'E and 27°45'00"–27°52'30"N (Figure 1).

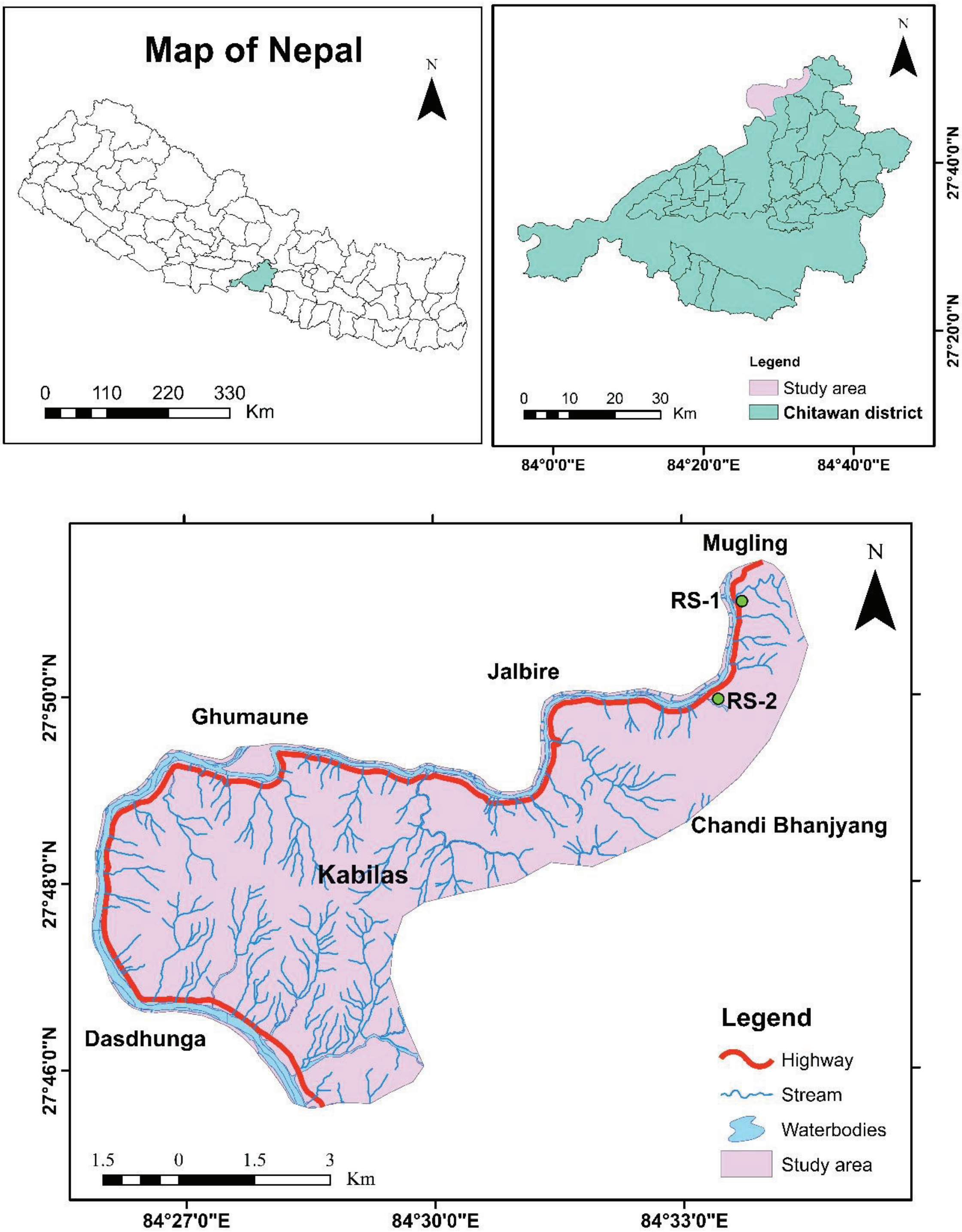

Figure 1, Location map showing the study area within Chitwan District, Central Nepal.

Geological condition

The corridor lies within the Mahabharat Synclinorium, characterized by tightly folded structures, sheared zones, and thrust faults. Lithostratigraphy resembles the Nawakot Complex (Paudyal, 2014) and includes Kuncha, Lower Siwalik, Fagfog Quartzite, Dandagaon Phyllite, Purebensi Quartzite, Amdanda Phyllite, Dhading Dolomite, and Benighat Slate (Figure 2). Dominant rocks are metasandstone, phyllite, dolomite, quartzite, slate, mudstone, sandstone, colluvium soil, and minor greenschist and hematite beds.

Elevations range from ~200 m in river valleys to 500 m along hills. The terrain is rugged, with steep slopes, deeply incised gorges, and variable lithology, creating conditions prone to slope instability.

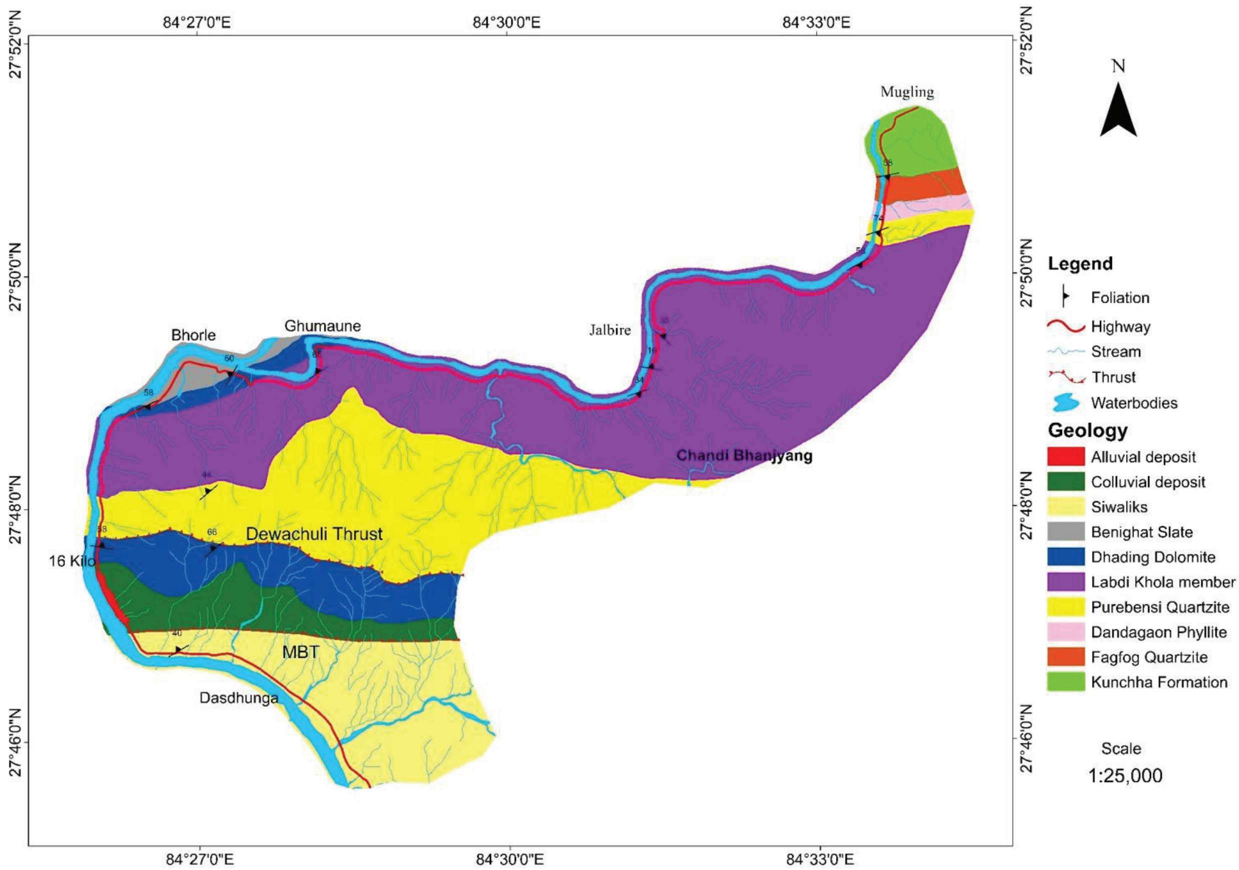

Figure 2, Geological map of the study area along the Narayangadh–Mugling Highway section (modified after Paudyal, 2014).

Methodology

Field investigation

The two slopes, RS-1 and RS-2, were selected as representative high-risk sites based on a combination of field observations and historical data (Figure 3). Field investigations recorded slope geometry, discontinuity characteristics (orientation, spacing, persistence, aperture, infill, weathering), groundwater, and hydrological influences, providing essential input for RMR_{basic}, SMR, and kinematic analyses.

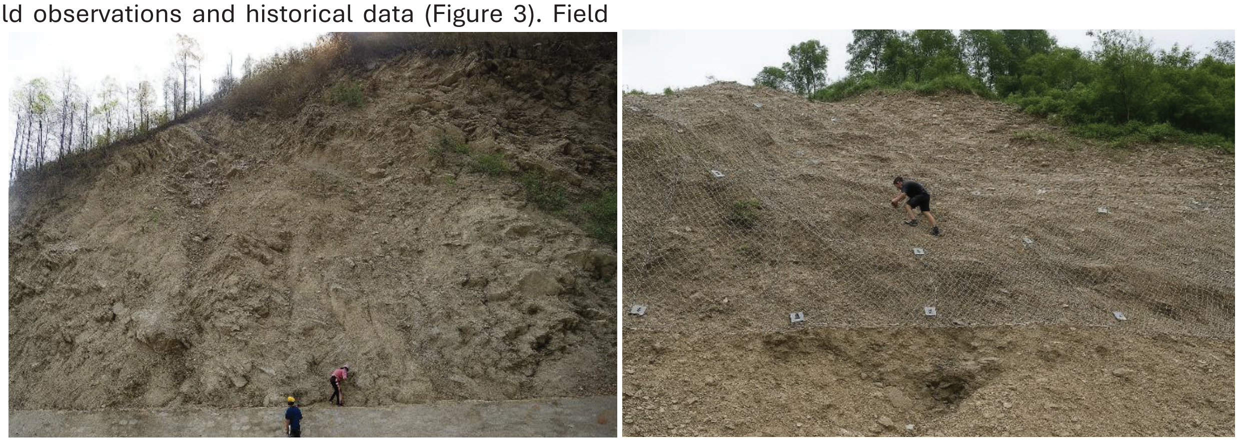

Figure 3, Field photographs of rock-cut slopes

Laboratory testing

Rock samples underwent Point Load Index testing (50 samples) to determine intact rock strength. Results were used to derive cohesion, friction angle, and unit weight.

Data analysis

RMR_{basic}: Based on intact rock strength, RQD, discontinuity spacing/condition, and groundwater (Bieniawski, 1973). Orientation parameters excluded.

$$RQD = 115 - 3.3J_v \quad (1)$$

$$(Jv\ between\ 4 - 44; empirical\ approximation)$$

$$SMR = RMR_{basic} + (F1 \times F2 \times F3) + F4 \quad (2)$$

Factors F1-F3 account for slope-discontinuity orientation; F4 accounts for excavation method.

Stability analysis

Stability analyses were conducted using SLIDE 5.0 with the Morgenstern–Price method to evaluate vertical slice equilibrium for both circular and non-circular failure surfaces. Input parameters included unit weight (γ), cohesion (c), friction angle (ϕ), groundwater conditions, and detailed slope geometry. Critical slip surfaces were identified through an automated search algorithm, and rock anchors were modeled considering their length, spacing, orientation, and capacity.

Results and discussion

For detailed analysis, two of the most vulnerable rock-cut slopes along the Narayangadh–Mugling Highway section in the Lesser Himalaya region of central Nepal were selected. The rock masses in this area are heavily jointed, typically exhibiting two to three dominant joint sets. Field investigations thoroughly examined discontinuity characteristics affecting slope stability, including orientation, spacing, persistence, aperture, roughness, infilling, and weathering. These data informed kinematic and limit equilibrium analyses alongside rock mass classification using the Rock Mass Rating (RMR) and Slope Mass Rating (SMR) systems.

Discontinuity spacing, defined as the perpendicular distance between adjacent joints, controls block size and influences permeability and seepage within the rock mass. Measurements of spacing and other discontinuity conditions were carefully recorded and averaged for RMR calculation. Although the study was conducted in the dry season with negligible groundwater presence, seasonal variations may affect hydrological conditions.

Rock mass classification

RMR_{basic} values were computed by summing parameter ratings, classifying both slopes (RS-1 and RS-2) within the fair rock category (Class III) with scores of 58 and 48, respectively. Table 1 summarizes the parameter ratings and classifications for the slopes investigated.

Kinematic analysis

Kinematic analysis of RS-1 and RS-2 demonstrates that slope stability is strongly influenced by the orientation of discontinuities relative to the slope face.

Discontinuity orientation is a critical factor influencing structurally controlled failure modes in jointed rock masses. During field investigations, the relative orientations of slopes and discontinuities were measured and stereographically projected to qualitatively assess whether the orientation adjustment factors are favorable or unfavorable for stability.

Table 1, Rock Mass Rating (RMR_{basic}) values for RS-1 and RS-2

Slopes	RS-1	RS-2
Strength of intact rock (R1)	7	7
RQD	13	8
Spacing of discontinuity (R3)	10	8
Condition of discontinuity (R4)	13	10
Groundwater condition (R5)	15	15
RMR_{basic}	58	48
Class	III	III
Grading	Fair	Fair

The most critical discontinuity set, together with slope face orientation, was used to calculate factorial adjustment factors (F1, F2, and F3). Bieniawski's Rock Mass Rating (RMR), based on RMR_{basic}, was modified to the Slope Mass Rating (SMR) by incorporating these factors. Additionally, excavation-related adjustment factor F4 was determined through detailed visual inspection at each site.

The SMR values accounting for toppling and planar failure modes, slope-discontinuity relationships, and excavation method yielded a classification of fairly stable Class III with an SMR of 50 for RS-1, and unstable Class IV with an SMR of 40 for RS-2 (Table 2).

Table 2, Slope Mass Rating (SMR) values for RS-1 and RS-2 (Failure mode T = Toppling; P = Planar)

Slopes	RS-1		RS-2
Failure	T	W	T
F1*F2*F3	0	0	0
F4	-8	-8	-8
RMR	58	58	48
SMR	50	50	40
Class	III	III	IV
Stability	PS	PS	UN
Probability of failure	0.4	0.4	0.6

RS-1 shows potential for both toppling and wedge failures, while RS-2 is more critically affected, with a higher likelihood of toppling failure. These findings underscore the role of joint set orientation and slope geometry in controlling failure mechanisms and provide a basis for selecting suitable stabilization measures (Figure 4).

Geotechnical properties

The investigated rock slopes show moderate weathering and are primarily composed of slate, phyllite, gritty phyllite, and metasandstone. The rock masses are extensively fractured and jointed, influencing their mechanical behavior. Laboratory point load tests were conducted to assess the intact rock strength indices for slopes RS-1 and RS-2. Complementary geomechanical parameters, including cohesion and internal friction angles, were derived using the RocLab software (Figure 5). The comprehensive geotechnical properties of both slopes are detailed in Table 3.

Stability analysis and result

A detailed stability assessment of the selected rock slopes was carried out using SLIDE 5.0, applying the Morgenstern and Price method to compute the factor of safety (FoS). This quantitative analysis was complemented by qualitative evaluations using the RMR and SMR classifications, providing a comprehensive understanding of slope stability. Under dry conditions, the FoS values for RS-1 and RS-2 were calculated as 0.96 and 0.81, respectively, both well below the acceptable threshold of 1.0. These results indicate that the slopes are critically unstable, with a high likelihood of failure under existing conditions. Consequently, immediate reinforcement measures and continuous monitoring are essential to mitigate risks and ensure long-term slope safety.

The assessment further reveals that several rock-cut slopes along the Narayangadh–Muglingg road are unstable during the dry season, with failure potentially occurring at any time (Figure 6). The observed and anticipated failure mechanisms include planar sliding along persistent discontinuities, wedge failures at the intersection of joint sets, toppling of isolated blocks, and circular failures associated with weathered rock masses. These instabilities are exacerbated by the presence of highly weathered rock, weak overburden materials, and unfavorable discontinuity orientations, all of which collectively increase the susceptibility of the slopes to failure. Such conditions pose a significant hazard to road safety and highlight the urgent need for systematic stabilization and monitoring measures.

Both qualitative and quantitative approaches consistently indicate marginal stability of the investigated slopes. According to the SMR classification, RS-1 is rated as “Partially Stable,” whereas RS-2 is classified as “Unstable,” in agreement with the low FoS values obtained from the SLIDE analysis. This consistency between empirical classification and numerical modeling confirms that both slopes are highly susceptible to failure under the current conditions.

These results highlight the need for targeted slope stabilization measures. Potential interventions include controlled slope re-profiling to reduce steepness, installation of rock anchors or bolts to enhance cohesion, construction of retaining structures, drainage improvements to limit water-induced weakening, and routine monitoring to detect early signs of instability.

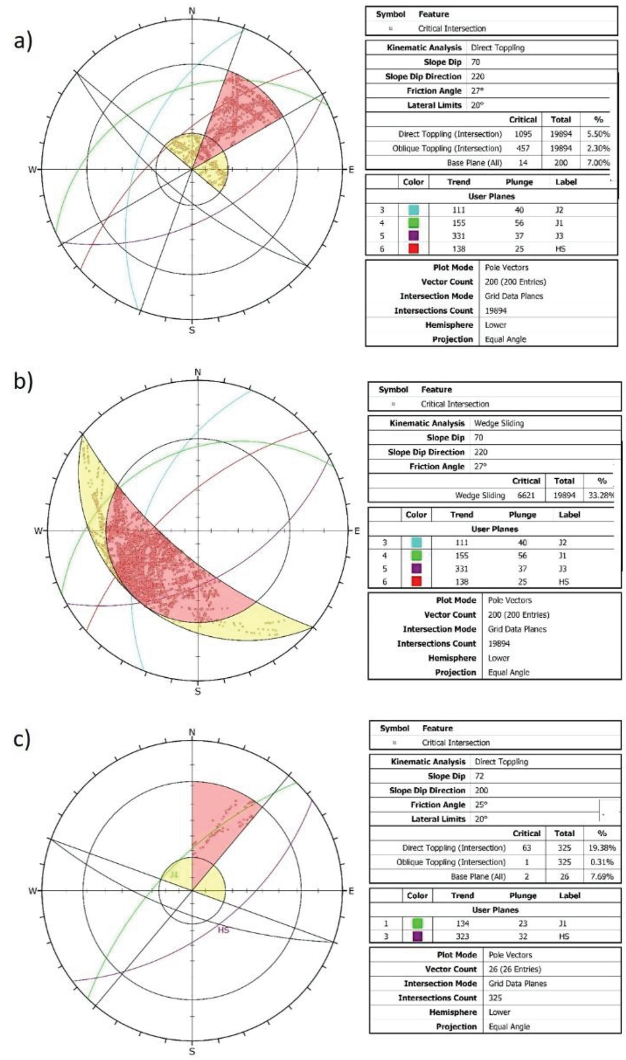

Figure 4, (a) and (b) Kinematic analysis results for slope RS-1 showing toppling and wedge failure modes; (c) Kinematic analysis results for slope RS-2 indicating toppling failure susceptibility

Table 3, Geotechnical properties of slope materials 2

Slopes	RS-1	RS-2
Avg. slope angle (^{O})	70	71
Cohesion (MPa)	0.089	0.077
Friction angle (^{O})	27.09	25.31
Unit weight (KN/m^3)	20	19
Point load strength index (MPa)	3.74	3.38

In this study, the effectiveness of rock anchor installation and slope re-profiling was examined in detail, demonstrating their capability to improve slope stability. Incorporating these measures within a slope-specific risk assessment framework can markedly enhance road safety and reduce both economic and human losses from slope failures. For critical slopes and lifeline structures, such as major highways, dams, railways, and urban slopes, a higher margin of stability is required. Accordingly, the factor of safety (FoS) is typically designed to be greater than 1.5 to account for the potentially severe consequences of failure (Hoek and Bray, 1981; Duncan et al., 2005).

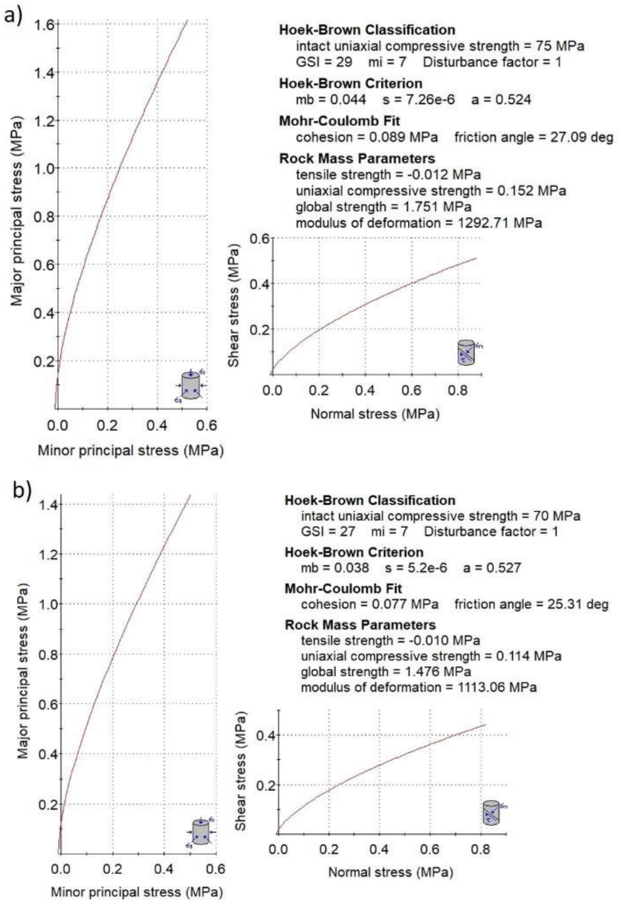

Figure 5, (a) Geomechanical parameters derived for slope RS-1 including cohesion, friction angle, unit weight, and point load strength index; (b) Geomechanical parameters determined for slope RS-2.

Effect of rock anchors on slope stability

The influence of rock anchors on slope stability was analyzed using SLIDE 5.0, with anchor parameters defined in terms of type, length, spacing, orientation, and capacity. The modeled end anchors had lengths of 12 m and 15 m, with capacities of 400 kN and 500 kN. Anchors were spaced at 1 m along the slope, with an out-of-plane spacing of 1 m. They can be installed at inclinations of −90°, −120°, −150°, and −180° relative to the horizontal slope face, where negative angles indicate inclinations measured downward from the horizontal, with larger negative values corresponding to steeper orientations pointing back into the slope. Stability analyses indicated that an installation angle of −150° provided the highest improvement in factor of safety (FoS = 1.55 for RS-1 and 1.53 for RS-2), outperforming other tested orientations (FoS range: 0.46–1.27 for RS-1; 0.39–1.15 for RS-2). Details are shown in Table 4 and Figure 7. This orientation was particularly effective for slopes dipping near 70°, optimizing load transfer and enhancing resistance against potential failure planes. The results align with Baharvand et al. (2015), who reported −150° as the optimal inclination for slopes around 60° and −165° for slopes near 75°.

The required anchor capacities were determined based on the stabilizing forces necessary to achieve the target factor of safety (FoS) calculated in SLIDE. For slope RS-1, anchors were designed with a capacity of 100 kN, reflecting their relatively lower stabilization requirement, while RS-2 required 350 kN anchors due to higher instability. These capacities were verified assuming an anchor FoS greater than 1.8, ensuring that each anchor could adequately resist anticipated loads from potential planar or toppling failure mechanisms. The design considered slope geometry, rock mass strength, and potential failure surfaces, providing sufficient reinforcement without unnecessary overdesign.

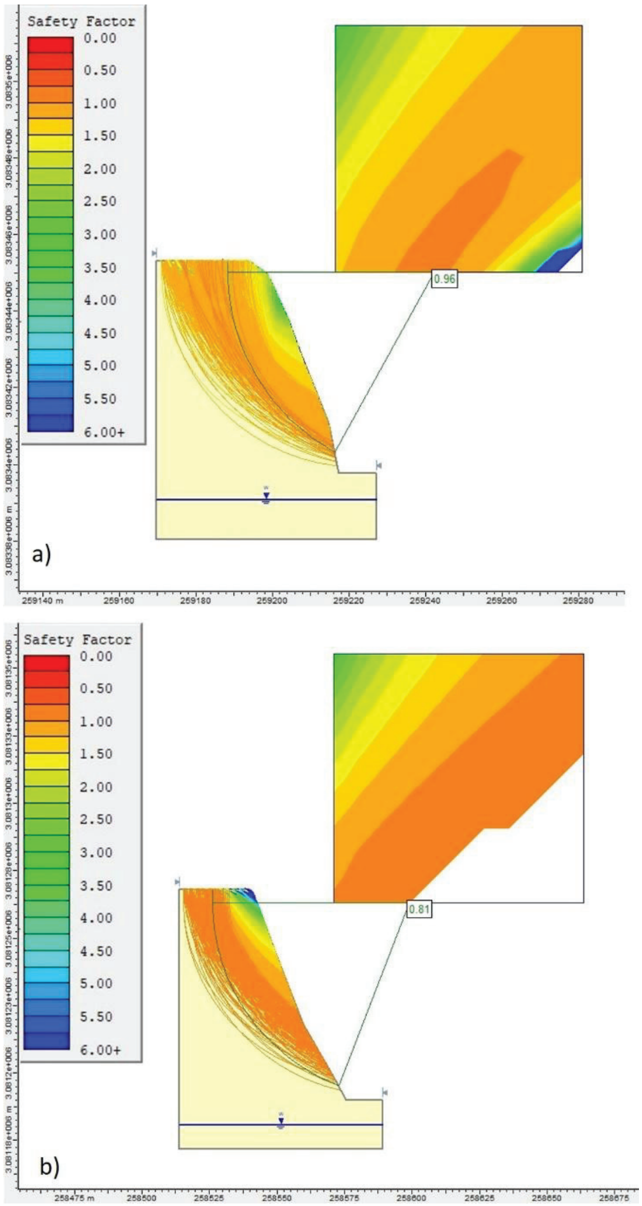

Figure 6, (a) Stability analysis results showing the factor of safety for rock-cut slope RS-1 using SLIDE software; (b) Stability analysis results for rock-cut slope RS-2.

Influence of cut slope angle on rock slope stability

The influence of cut slope angles on stability was analyzed using SLIDE 5.0 by modeling slopes with dip angles of 45°, 50°, 55°, and 60°. Factors of safety (FoS) were computed for each configuration (Table 5). Results indicate that the 45° bench-cut slope exhibited higher stability compared to the others (Figure 8).

Table 4, Stability results after rock anchor installation

Slopes	RS-1				RS-2			
Anchor type	End anchored				End anchored			
Anchor length (m)	12				15			
Distance between anchors (m)	1				1			
Out-of-plane spacing (m)	1				1			
Anchor capacity (kN)	400				500			
Anchor direction from horizontal (°)	-90	-120	-150	-180	-90	-120	-150	-180
FoS before rock anchor	0.96	0.96	0.96	0.96	0.81	0.81	0.81	0.81
FoS after rock anchor	0.46	1.20	1.55	1.27	0.39	1.01	1.53	1.15

Implementing a 45° slope requires substantially more excavation, increasing construction costs, material handling, and environmental disturbance. Thus, only slope re-profiling is not enough to stable these cut slopes along the Narayangadh-Mugling Road section. But by integrating a 60° slope with strategically designed rock anchors, sufficient stability can be achieved without incurring the high costs and operational challenges associated with a gentler 45° slope.

A qualitative cost–benefit evaluation suggests that a 60° cut slope reinforced with rock anchors achieves an effective balance among safety, constructability, and long-term maintenance requirements (Figure 9; Table 6). For steeper slopes nearing 70°, this design approach optimizes both structural performance and economic efficiency, providing a practical solution for slope stabilization in challenging terrains.

Table 5, Stability results after cut slope reprofiling

Slope	Suitable cut angle (o)	FoS before slope refiling	FoS before slope refiling
RS-1	45 (1H:1V)	0.96	1.7
	50 (1H:1.16V)	0.96	1.57
	55 (1H:1.43V)	0.96	1.48
	60 (1H:1.73V)	0.96	1.39
RS-2	45 (1H:1V)	0.81	1.35
	50 (1H:1.16V)	0.81	1.25
	55 (1H:1.43V)	0.81	1.17
	60 (1H:1.73V)	0.81	1.1

Design life and maintenance considerations

The proposed stabilization measures, particularly rock anchors and slope reprofiling, are expected to achieve a design life of 20–30 years when implemented with adequate corrosion protection and strict quality control. Their long-term performance depends on a structured maintenance program, including periodic anchor head inspections, re-tensioning as required, and routine cleaning and repair of drainage systems. Post-event inspections after intense rainfall or seismic activity are also critical to ensure continued stability. Integrating these maintenance provisions enhances both the durability and cost-effectiveness of the proposed solutions' description.

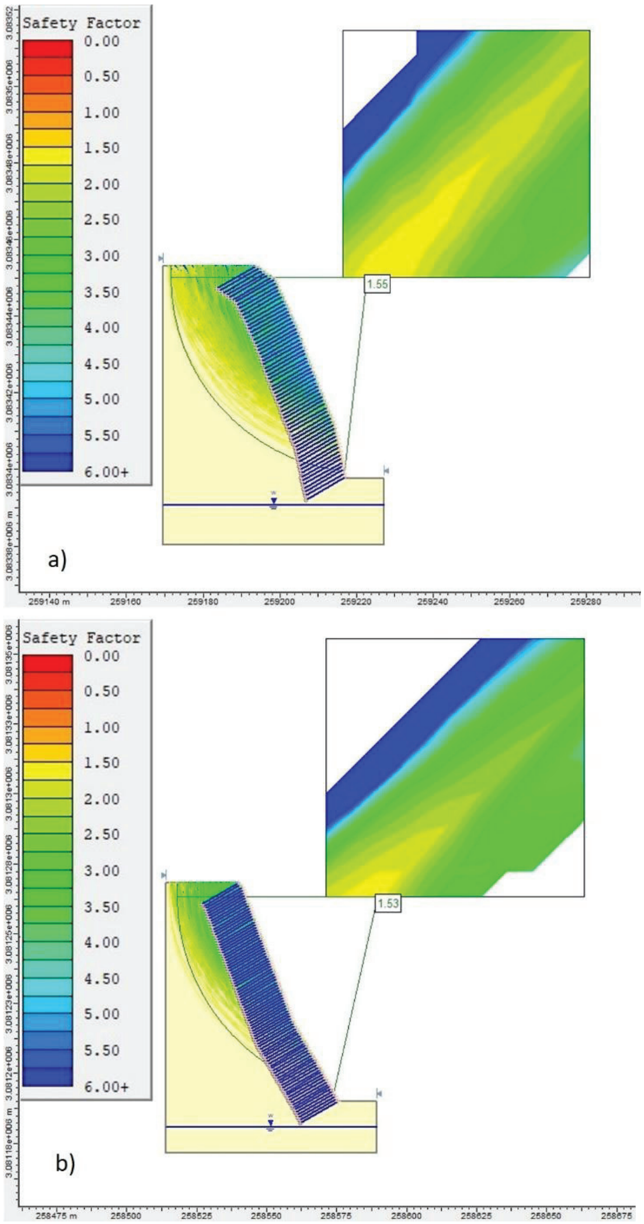

Figure 7, (a) Stability analysis of rock-cut slope RS-1 after installation of rock anchors showing improved factor of safety; (b) Stability analysis of rock-cut slope RS-2 after installation of rock anchors demonstrating enhanced slope stability.

Conclusions

Roadside rock-cut slopes along the Narayangadh–Mugling Highway, central Nepal, are highly susceptible to planar, wedge, toppling, and circular failures. Field investigations and modeling confirm that slopes RS-1 and RS-2 are critically unstable (FoS < 1.0), in agreement with RMRbasic and SMR assessments.

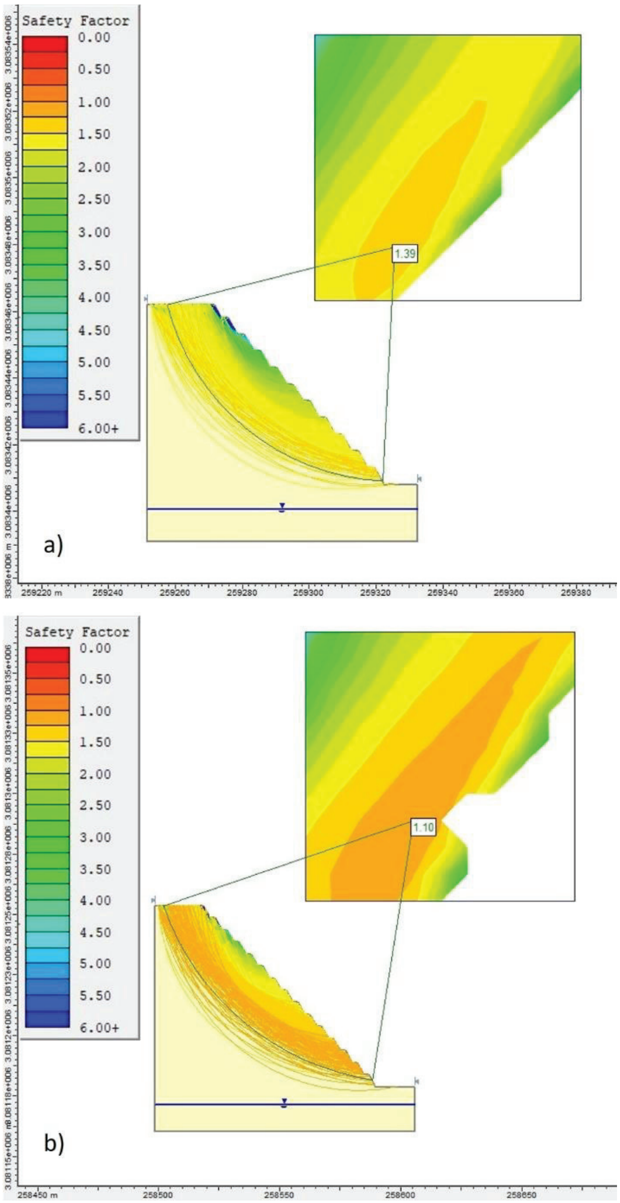

Figure 8, (a) Stability analysis results of rock-cut slope RS- 1 after slope inclination was modified to 60°; (b) Stability analysis results of rock-cut slope RS- 2 after slope inclination was modified to 60° (1H:1V)

Table 6, Stability analysis results after cut slope modification and anchor reinforcement

Slope	RS-1	RS-2
Anchor type	End anchored	End anchored
Anchor length (m)	5	10
Anchor length (m)	8	15
Distance between anchors (m)	1	1
Out-of-plane spacing (m)	1	1
Anchor capacity (KN)	200	300
Anchor direction from horizontal (0)	-150	-150
Slope Re-profiling	60	60
Pre-reprofiling and anchor FoS	0.96	0.81
Post-reprofiling and anchor FoS	1.56	1.51

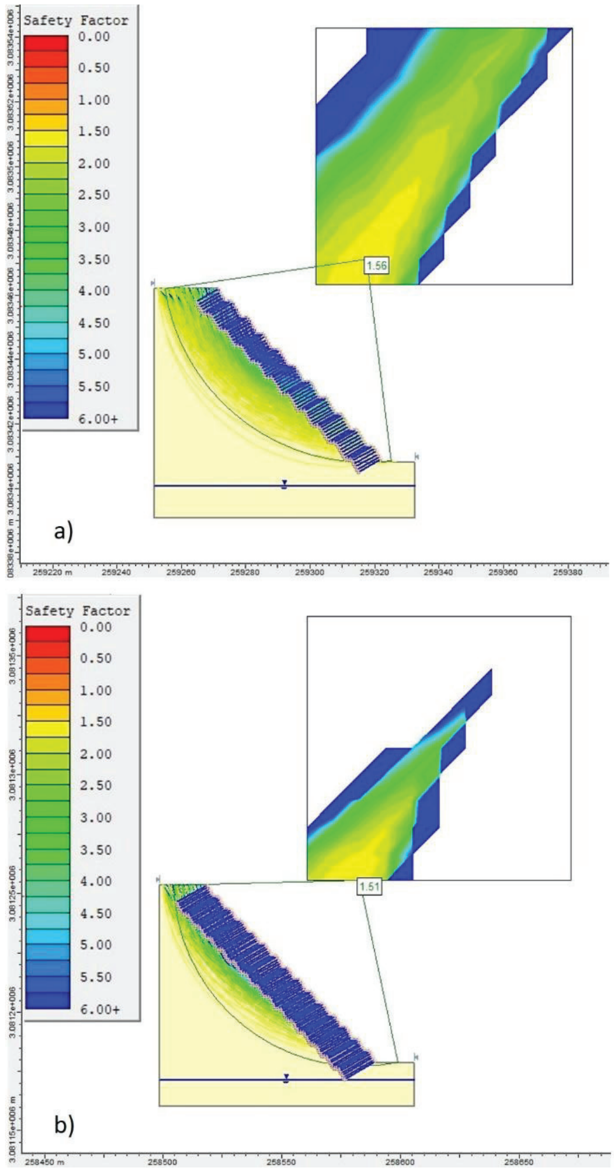

Figure 9, (a) Stability analysis of rock-cut slope RS-1 following slope reprofiling and rock anchor installation; (b) Stability analysis of rock-cut slope RS-2 following slope reprofiling and rock anchor installation.

Rock anchors (−150°, 8–15 m, 200–300 kN) effectively stabilize these slopes, offering a cost-efficient alternative to extensive re-profiling. A 60° slope with anchors achieves FoS up to 1.56 while minimizing excavation and environmental impact.

Key factors for sustainable stabilization include slope geometry, discontinuity orientation, and anchor design. Combined interventions, targeted re-profiling, rock anchors, benching, drainage, and monitoring—provide a practical framework for securing high-risk Himalayan Road slopes.

Limitations and future work

This study did not consider seismic loading, which is critical in the earthquake-prone Himalayan region. Future analyses incorporating dynamic forces could alter factors of safety assessments and rock anchor design, providing a more comprehensive evaluation of slope stability under combined static and dynamic conditions.

Acknowledgements

Special thanks to Geotech Solutions International for valuable support. We are thankful to two anonymous reviewers for their comments and suggestions, which helped to rectify the manuscript.

Author contributions

Shankar wrote the main manuscript text, Manita and Kabita prepared figures and revise the article. All authors also reviewed it.

Data availability

No datasets were generated or analyzed during this study.

Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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