

Kinematic and Numerical Stability Analysis of Landslide-Prone Slopes Selected from Susceptibility Mapping along the Malekhu–Mugling Section of Prithvi Highway, Nepal

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Abstract: The Malekhu–Mugling section of the Prithvi Highway traverses steep terrain where road-cut slopes are susceptible to instability. This study evaluates landslide-prone slopes using kinematic and numerical methods after preparing a GIS-based landslide susceptibility map. A landslide inventory was developed from field reconnaissance and Google Earth, and the frequency ratio (FR) method with fourteen conditioning factors generated a Landslide Susceptibility Index and five susceptibility classes. The model achieved AUC values of 0.774 for the success rate and 0.857 for the prediction rate. Five slopes were selected based on susceptibility, accessibility, and engineering relevance. Total-station surveys provided slope geometry, while discontinuity orientations and rock-mass information supported kinematic analysis in Dips. Planar, wedge, and flexural-toppling mechanisms were evaluated. Numerical stability was assessed using the finite element method (FEM) in PLAXIS 2D and Phase2 and the limit equilibrium method (LEM) in Slide using Janbu and GLE approaches. Wedge sliding was prominent at L2 and L3, while flexural toppling was pronounced at L5. Factors of safety (FoS) ranged from 2.424–5.813 in PLAXIS 2D, 2.460–6.720 in Phase2, 2.549–6.078 using Janbu, and 2.783–6.599 using GLE. The findings highlight susceptibility mapping followed by structural and numerical analysis for highway slope stability.

Keywords: Landslide susceptibility, Kinematic analysis, Rock slope stability, Finite element method, Limit equilibrium method, Prithvi highway

Introduction

Landslides are a recurrent hazard in the mountainous terrain of Nepal, where steep topography, complex geology, intense monsoonal rainfall, weathering, and road excavation interact to reduce slope stability (Regmi et al., 2013a; Khanal and Dahal, 2024). The Malekhu–Mugling section of the Prithvi Highway crosses rugged hills and deeply incised valleys, and slope failures can disrupt transportation and damage infrastructure. Regional susceptibility assessment is useful for identifying areas requiring detailed engineering investigation, but susceptibility does not directly quantify the mechanical stability or failure mechanism of an individual slope (Aleotti and Chowdhury, 1999).

GIS-based susceptibility mapping relates observed landslides to terrain, geological, hydrological, vegetation, and anthropogenic factors. In contrast,

kinematic analysis tests the geometric feasibility of structurally controlled rock failure, while finite element method (FEM) and limit equilibrium method (LEM) provide quantitative stability measures through deformation and factor of safety (Hoek and Bray, 1981; Duncan et al., 2005). The present study therefore uses the susceptibility map as the first-stage screening tool and focuses the engineering assessment on five representative slopes

Study area and methodology

The study covers approximately 40 km of the Malekhu–Mugling section in central Nepal, across Dhading and Chitwan districts. The terrain comprises steep hills, deeply incised valleys, variable lithology, and elevations of about 300 to more than 1,500 m. Annual rainfall is reported at about 1,500–2,000 mm, concentrated during the June–September monsoon. These conditions, together with road excavation and variable rock-mass quality, contribute to slope instability.

Field reconnaissance identified 28 landslides for inventory preparation. The inventory was supplemented by Google Earth interpretation and divided into training and testing subsets at 70:30. Fourteen conditioning factors, including slope, aspect, elevation, curvature, lithology, topographic indices, vegetation, and distances to roads, streams, and faults, were integrated using the frequency ratio (FR) method, an approach applied in landslide susceptibility studies in the Nepal Himalaya (Regmi et al., 2013b). The resulting susceptibility index was classified into five zones. The map guided selection of five representative slopes (L1–L5) for detailed investigation, emphasizing susceptible locations and observed engineering conditions.

Total-station surveys provided cross-sectional geometry; discontinuity dip and dip direction were measured with a geological compass; and rock samples were tested for uniaxial compressive strength. Rock mass rating (RMR) values ranged from 51 to 65, corresponding to fair to good rock mass (Bieniawski, 1989; Romana, 1985). Kinematic analysis was performed in Dips for planar, wedge, and flexural-toppling criteria following established rock-slope

kinematic principles (Hoek and Bray, 1981; Goodman, 1995; Umrao et al., 2011). Numerical models used surveyed geometry and rock-mass parameters. FEM analyses used shear-strength reduction in PLAXIS 2D and Phase2, while LEM analyses used Slide with Janbu and generalized limit equilibrium (GLE) methods (Duncan et al., 2005). The reported numerical models represent gravity-loading conditions; dynamic loading was not considered.

Results and discussion

The FR susceptibility model differentiated the corridor into very-low, low, moderate, high, and very-high classes covering 14.66%, 33.54%, 26.34%, 19.09%, and 6.37% of the mapped area, respectively. The success-rate and prediction-rate area-under-the-curve (AUC) values were 0.774 and 0.857. High-susceptibility clusters were reported around Krishna Bhir–Phishling and near Malekhu, Mugling, and Kuringhat. The susceptibility map was used as a screening framework for detailed site selection rather than as a direct factor-of-safety calculation, consistent with the distinction between susceptibility mapping and site-specific stability analysis (Aleotti and Chowdhury, 1999; Regmi et al., 2013b).

Kinematic analysis

Kinematic results varied with slope orientation, discontinuity geometry, and friction angle. L2 and L3 exhibited the largest proportions of potentially critical wedge intersections, 16.86% and 16.35%, respectively. L1 showed 2.56% potentially critical wedge cases, while L4 showed 4.16% wedge and 2% flexural-toppling cases. At L5, flexural toppling represented 56.25% of evaluated cases. The results indicate that the observed landslide condition cannot be interpreted from slope angle alone and that structural orientation must be evaluated with rock-mass and slope geometry (Hoek and Bray, 1981; Goodman, 1995; Umrao et al., 2011).

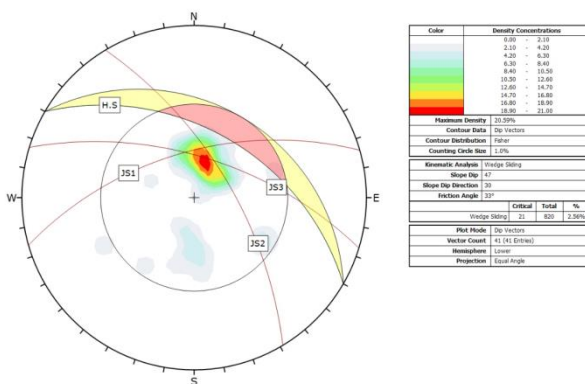


Figure 1, Representative Dips stereonet showing wedge-sliding kinematic analysis for L1.

Table 1, Summary of kinematic analysis at representative slopes.

Slope / dominant kinematic mode	Critical proportion (%)
L1 / Wedge	2.56
L2 / Wedge	16.86
L3 / Wedge	16.35
L4 / Wedge	4.16
L5 / Flexural toppling	56.25

FEM and LEM stability

Under the adopted static conditions, all five modeled slopes had factor of safety (FoS) values above 1.0. PLAXIS 2D produced FoS values of 2.822, 2.582, 3.658, 2.424, and 5.813 for L1–L5, while Phase2 produced 3.130, 2.705, 3.958, 2.460, and 6.720. L4 had the lowest FEM FoS, whereas L5 had the highest. The LEM results followed the same broad pattern: Janbu values ranged from 2.549 to 6.078 and GLE values from 2.783 to 6.599. These methods provide complementary equilibrium- and deformation-based perspectives on slope stability (Duncan et al., 2005).

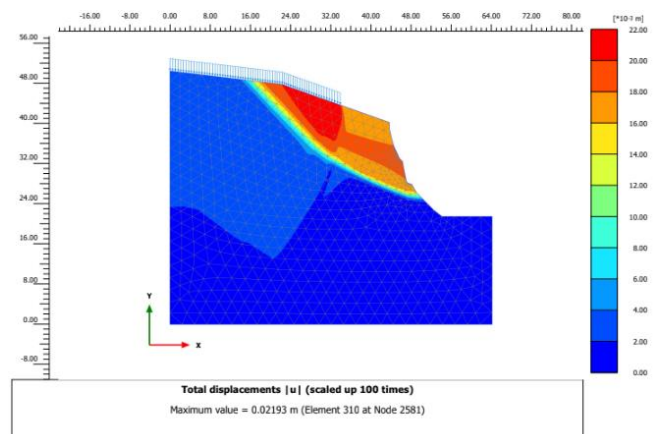


Figure 2, PLAXIS 2D total-displacement result for representative slope L1.

Table 2, Comparison of factor of safety from FEM and LEM analyses.

Slope	FEM FoS		LEM FoS	
	PLAXIS	Phase2	Janbu	GLE
L1	2.822	3.13	2.681	2.937
L2	2.582	2.705	2.549	2.78
L3	3.658	3.958	3.726	4.145
L4	2.424	2.46	2.974	3.182
L5	5.813	6.72	6.078	6.599

Limit equilibrium analysis and integrated interpretation

The LEM analyses complement the FEM results by evaluating equilibrium along potential failure surfaces. Janbu and GLE calculations show consistent relative

patterns across the five sites, with L5 having the largest FoS and L2 among the lowest values. The agreement between FEM and LEM indicates comparable stability trends, although numerical differences are expected because of different formulations, meshing, and solution procedures. The comparatively lower FoS at L2 and L4 warrants greater engineering attention within the investigated set.

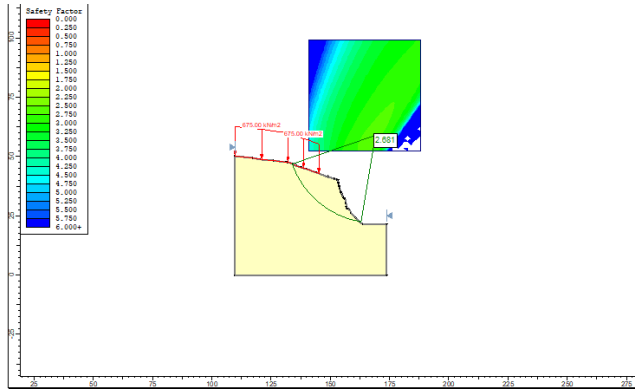


Figure 3, Janbu limit-equilibrium analysis for L1 (FoS = 2.681).

The integrated workflow is hierarchical: the susceptibility map identifies spatially susceptible portions of the corridor; field investigation establishes local geological and geometric conditions; kinematic analysis evaluates structurally feasible failure mechanisms; and FEM/LEM quantify stability under selected modeling assumptions. This combination avoids treating a regional susceptibility value as a site-specific factor of safety and provides a practical framework for prioritizing detailed highway-slope investigation.

Conclusions

The study demonstrates an integrated procedure for moving from regional landslide susceptibility assessment to detailed slope-stability analysis along the Malekhu–Mugling section of the Prithvi Highway. The FR susceptibility map differentiated the corridor into five susceptibility classes and produced AUC values of 0.774 for the success rate and 0.857 for the prediction rate. The map served primarily as a spatial screening tool for selecting representative slopes for engineering analysis rather than as a direct measure of mechanical stability.

Detailed investigation of five representative slopes showed RMR values of 51–65, indicating fair to good rock-mass conditions. Kinematic analysis identified wedge sliding as the most prominent geometrically feasible mechanism at L2 and L3, while L5 showed a strong flexural-toppling tendency. FEM and LEM results produced FoS values above unity for all modeled slopes under the adopted static conditions, with PLAXIS 2D values of 2.424–5.813 and Phase2 values of 2.460–6.720. Janbu and GLE results also showed consistent stability trends. The results emphasize that factor of safety and failure mechanism provide complementary

information: a slope may have a comparatively high static FoS while still possessing a geometrically feasible structurally controlled mechanism.

The study therefore supports the use of susceptibility mapping for regional screening followed by field-based kinematic and numerical analysis for site-specific engineering decisions. However, the numerical results remain conditional on the adopted material properties, simplified rock-mass representation, groundwater assumptions, and static loading. Further assessment should incorporate rainfall-induced pore-pressure changes, seismic loading, and improved characterization of heterogeneous and discontinuous rock masses before final stabilization design.

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