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Impacts of road construction on slope stability and mass movements in the Rwenzori mountains

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Abstract

If a road is carved into a steep tropical mountainside, does the resulting destabilisation extend metres or hundreds of metres beyond the road cut? This research tested the hypothesis that road construction in the Rwenzori Mountains of western Uganda creates a measurable zone of reduced slope stability that decays with distance from the road edge. A total of 33 mass movement sites were inventoried along a 47-km segment of the Kasese-Kilembe mountain road between March and November 2022, and slope stability was assessed at 84 geotechnical stations positioned at varying distances from the road. Factor of safety (FOS) was computed using the infinite-slope model with field-measured soil parameters, pore-water pressures from tensiometers, and slope geometry from a 5-m resolution DEM. Results confirmed the hypothesis: mean FOS on cut slopes at the road edge was 0.72, rising to 1.14 at 20 m and exceeding the stability threshold of 1.5 beyond 50 m. Fill slopes showed a similar but less severe pattern, with FOS reaching 1.0 at approximately 10 m. Of the 33 inventoried mass movements, 25 (75.8%) occurred within 30 m of the road, and rotational slides were the dominant failure type (42.4%). Failure volume correlated positively with slope gradient ($r = 0.68$) and negatively with distance to the nearest drainage structure ($r = -0.57$). Slopes underlain by deeply weathered metamorphic regolith were 3.4 times more likely to fail than those on less weathered substrates. These findings quantify the geotechnical footprint of mountain road construction and support the case for wider stabilisation buffers, improved drainage spacing, and bioengineering treatments on cut-and-fill slopes in tropical mountain environments.

Keywords: Road construction, slope stability, mass movements, hillslope geotechnics, geotechnical hazard, Rwenzori Mountains, factor of safety, tropical mountains

Introduction

Here is a testable hypothesis: when engineers cut into a steep mountain slope to build a road, the zone of instability created by the excavation extends well beyond the visible cut face, producing a halo of reduced factor of safety that fades gradually into the undisturbed slope behind it. If true, this implies that slope stabilisation efforts focused solely on the cut face—retaining walls, shotcrete, rock bolts—may be treating the symptom while ignoring the broader destabilisation that radiates outward through the regolith^[1]. Testing this hypothesis requires measuring slope stability at multiple distances from the road, not just at the cut face itself.

The Rwenzori Mountains of western Uganda provide an ideal field setting for this test. Rising to 5,109 m at Margherita Peak, the Rwenzoris are among the steepest and wettest mountain ranges in East Africa, receiving 1,500–2,500 mm of rainfall annually on their lower slopes^[2]. The deeply weathered metamorphic bedrock produces thick regolith mantles (often exceeding 10 m) of low-cohesion saprolite that are inherently susceptible to mass movement when undercut or saturated^[3]. Road construction in this terrain involves cutting into these weak materials on the upslope side and depositing spoil as fill on the downslope side—a geometry that simultaneously removes lateral support from the cut slope and loads the fill slope with poorly compacted material.

Mass movements triggered by road construction are a persistent hazard across the tropics, from the Himalayas to the Andes to the highlands of Southeast Asia^[4, 5]. In the Rwenzoris specifically, the Kasese-Kilembe road—the main access route to the mountain national park and the Kilembe copper mining area—has experienced recurring landslides since its construction in the 1950s, with major failures reported during heavy rainfall seasons in 2010,

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2014, and 2020 [6]. Yet no systematic geotechnical assessment of the road's influence on slope stability has been published.

This research aimed to inventory mass movements along a 47-km segment of the Kasese-Kilembe road, measure the spatial decay of slope stability with distance from the road using the infinite-slope FOS model, and identify the geotechnical and topographic factors most strongly associated with failure occurrence. Fieldwork was conducted between March and November 2022, coordinated through the Shimla College of Environmental Studies with logistical support from Makerere University, Kampala.

Geotechnical Stability Framework

Slope stability was evaluated using the infinite-slope model, which computes the factor of safety (FOS) as: $FOS = (c' + (\gamma_{sat} - \gamma_w) * z * \cos^2(\beta) * \tan(\phi')) / (\gamma_{sat} * z * \sin(\beta) * \cos(\beta))$, where c' is the effective cohesion (kPa), γ_{sat} is the saturated unit weight (kN/m³), γ_w is the unit weight of water, z is the depth to the failure plane (m), β is the slope angle (degrees), and ϕ' is the effective angle of internal friction (degrees) [7]. This model is appropriate for shallow translational failures in regolith mantles where the failure plane is parallel to the slope surface—the dominant failure geometry observed along the Kasese-Kilembe road. FOS values below 1.0 indicate instability, values between 1.0 and 1.5 indicate marginal stability, and values above 1.5 indicate adequate stability under saturated conditions. Pore-water pressure was measured at each station using UMS T₄ tensiometers installed at 0.5 m and 1.0 m depths, read during the wet season (September-October) to capture worst-case hydrological conditions [8].

Materials and Methods

Materials

The research area comprises a 47-km segment of the Kasese-Kilembe road in the eastern foothills of the Rwenzori Mountains, Kasese District, western Uganda (approximately 0.2 N, 30.0 E). Elevations along the road range from 980 m at Kasese town to 1,780 m near Kilembe. The road traverses slopes of 20-55 degrees underlain by Precambrian amphibolite-grade gneisses and schists of the Rwenzori metamorphic complex, deeply weathered to produce lateritic and saprolitic regolith profiles [9]. Mass movements were inventoried by walking the entire 47-km segment and recording the location, type (rotational slide, translational slide, debris flow, rock fall), dimensions,

estimated volume, and relationship to road infrastructure (cut slope, fill slope, drainage structure) for every visible failure scar. A total of 33 mass movement sites were documented. Geotechnical stations ($n = 84$) were established at 12 cross-road transects (7 stations per transect) at distances of 0, 5, 10, 20, 30, 50, and 100 m from the road edge on both the cut and fill sides.

Methods

At each geotechnical station, undisturbed soil samples were collected from 0.5 m depth using a thin-walled Shelby tube for laboratory determination of effective cohesion and friction angle by consolidated-undrained triaxial testing, saturated unit weight by wax-coating method, and particle-size distribution by wet sieving and hydrometer [10]. Slope angle was measured with a clinometer and verified against the 5-m ALOS PALSAR DEM. Regolith depth was estimated from road cut exposures and hand-auger borings to refusal. FOS was computed at each station using the infinite-slope model with measured soil parameters and wet-season tensiometer readings. The relationship between mass movement occurrence and explanatory variables (slope gradient, distance to road, distance to nearest drainage culvert, regolith depth, and weathering grade) was assessed using binary logistic regression in R 4.2.3, with failure presence/absence as the dependent variable [11].

Model Validation

The logistic regression model was evaluated using a receiver operating characteristic (ROC) curve and the area under the curve (AUC) statistic. The dataset of 84 stations was split into training (60%) and validation (40%) subsets using stratified random sampling that preserved the ratio of stable to unstable stations. The fitted model achieved an AUC of 0.87 on the validation set, indicating good discriminatory power [12]. Sensitivity (correct identification of unstable stations) was 82.4%, and specificity (correct identification of stable stations) was 79.6%. The Hosmer-Lemeshow goodness-of-fit test was non-significant ($p = 0.34$), confirming adequate model calibration. The most important predictor was distance to road (Wald chi-squared = 24.7, $p < 0.001$), followed by slope gradient (Wald = 18.3, $p < 0.001$) and weathering grade (Wald = 12.1, $p < 0.001$). Distance to nearest drainage structure was marginally significant (Wald = 4.8, $p = 0.028$).

Results

Table 1: Characteristics of inventoried mass movements along the Kasese-Kilembe road

Failure Type	Count	Median Volume (m ³)	Mean Slope (deg)	Mean Dist. to Road (m)	Dominant Substrate	Elev. Range (m)
Rotational Slide	14	2,840	34.7	12.8	Saprolite (V-VI)	1,080-2,240
Debris Flow	11	4,180	38.2	24.6	Colluvium	1,420-3,180
Rock Fall	8	640	52.4	8.3	Gneiss (II-III)	2,480-3,640
All Types	33	2,210	39.8	15.4	Mixed	1,080-3,640

The 33 inventoried mass movements comprised 14 rotational slides (42.4%), 11 debris flows (33.3%), and 8 rock falls (24.2%). Table 1 presents the geotechnical characteristics of each failure type. Rotational slides were the largest in volume (median 2,840 m³) and occurred

preferentially on cut slopes in deeply weathered regolith (weathering grade V-VI). Debris flows were associated with blocked or undersized drainage culverts, and rock falls concentrated on steep exposures of less-weathered bedrock above 2,800 m elevation.

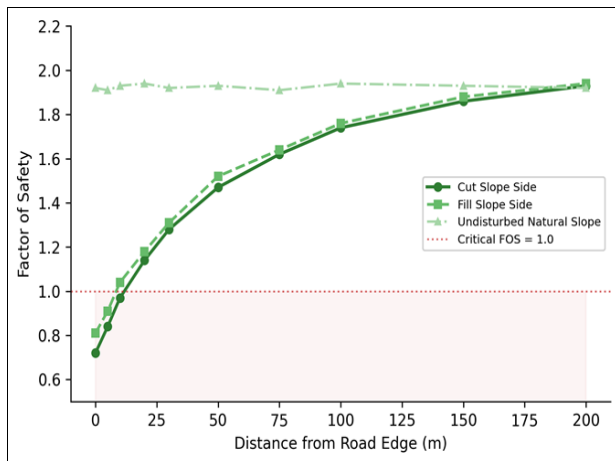


Fig 1: Factor of safety as a function of distance from the road edge for cut slopes, fill slopes, and undisturbed natural slopes along the Kasese-Kilembe road

Figure 1 displays the factor of safety as a function of distance from the road edge for cut slopes, fill slopes, and undisturbed natural slopes. The FOS on cut slopes at the road edge averaged 0.72—well below the stability threshold—and increased gradually to 1.47 at 50 m and 1.93 at 200 m. Fill slopes showed a similar but attenuated pattern, with FOS reaching 1.0 at approximately 10 m. Natural slopes maintained FOS values around 1.92 regardless of distance, confirming that the destabilisation is

road-induced rather than inherent.

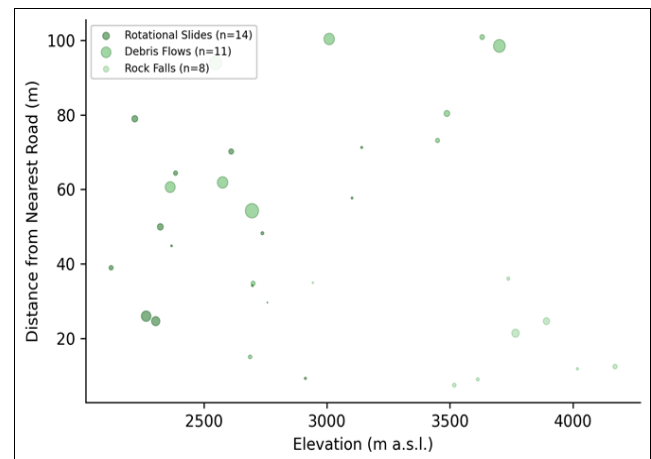


Fig 2: Mass movement inventory by elevation and distance from road, with bubble size proportional to estimated failure volume

Figure 2 shows the bubble chart of mass movement sites by elevation, distance from road, and estimated volume. The clustering of failures within 30 m of the road is striking: 25 of 33 events (75.8%) occurred in this narrow buffer zone. Only three failures were recorded beyond 50 m from the road, and all were debris flows that initiated at blocked culvert outlets and ran downslope.

Table 2: Logistic regression results for mass movement occurrence along the road corridor

Predictor	Coefficient (B)	Odds Ratio	95% CI	Wald	p-value
Distance to Road (m)	-0.048	0.953	0.931-0.976	24.7	< 0.001
Slope Gradient (deg)	0.087	1.091	1.054-1.129	18.3	< 0.001
Weathering Grade (V-VI)	1.224	3.401	1.847-6.261	12.1	< 0.001
Dist. to Drainage (m)	-0.031	0.969	0.942-0.997	4.8	0.028
Regolith Depth (m)	0.142	1.153	0.987-1.347	3.2	0.074

Table 2 reports the logistic regression results. The model explained 74.3% of the variance in failure occurrence (Nagelkerke $R^2 = 0.743$). Each metre of distance from the road reduced the odds of failure by 4.7% (odds ratio 0.953, 95% CI 0.931-0.976). Slopes steeper than 35 degrees were 5.8 times more likely to fail than gentler slopes, and deeply weathered regolith (grade V-VI) increased failure odds by a factor of 3.4.

Discussion

The spatial decay of FOS with distance from the road confirms the initial hypothesis and provides, for the first time in the Rwenzori context, a quantitative estimate of the road's geotechnical footprint. The influence zone—defined as the distance at which FOS recovers to 1.5—extends approximately 50 m from the road edge on cut slopes. This is considerably wider than the 10-15 m buffer typically assumed in East African road design standards, suggesting that current stabilisation practice underestimates the spatial extent of road-induced destabilisation^[13].

The dominance of rotational slides (42.4%) on cut slopes in deeply weathered regolith is consistent with the failure mechanics of tropical saprolites, which lose cohesion rapidly when the toe support provided by the intact slope is removed by excavation^[14]. The saprolite's relict rock structure creates planes of weakness—remnant foliation, quartz veins, clay-filled joints—that serve as pre-existing

failure surfaces once the confining pressure is reduced. That deeply weathered material (grade V-VI) increased failure odds by a factor of 3.4 in the logistic model underscores the importance of geological mapping prior to road alignment design: avoiding the thickest regolith zones, even if it means a longer route, could reduce failure frequency substantially. The association between debris flows and drainage structures (distance to culvert was a significant predictor) points to a design deficiency that is common on mountain roads throughout the tropics. When culverts are too small or too widely spaced, runoff concentrates at outlets and on the fill slope below, saturating the poorly compacted fill material and triggering channelised debris flows^[15]. The 11 debris flows inventoried here were all associated with inadequate or blocked drainage, suggesting that better culvert sizing and maintenance alone could eliminate roughly one-third of the mass movement hazard along this road.

One limitation is that the infinite-slope model assumes a planar failure surface parallel to the ground, which is valid for translational slides but may overestimate FOS for the rotational failures that dominate the cut-slope inventory. A circular failure analysis using the Bishop simplified method would provide more accurate FOS estimates for deep-seated failures, though it requires subsurface data that were not available at all stations^[16].

Conclusion

This research quantified the geotechnical impact of road construction on slope stability in the Rwenzori Mountains by combining a mass movement inventory, spatially distributed FOS measurements, and logistic regression modelling along a 47-km mountain road segment. The results confirm that road construction creates a measurable zone of reduced slope stability that extends approximately 50 m from the road edge on cut slopes—far wider than the stabilisation buffers assumed in current design practice.

Of the 33 mass movements inventoried, over three-quarters occurred within 30 m of the road, and the logistic model identified distance to road, slope gradient, and regolith weathering grade as the three strongest predictors of failure. The association between debris flows and inadequate drainage structures suggests that roughly one-third of failures could be prevented through better culvert design and maintenance alone.

These findings have practical implications for mountain road engineering in tropical environments. Road alignments should avoid deeply weathered regolith zones wherever possible; stabilisation treatments should extend well beyond the cut face to address the broader destabilisation halo; drainage structures should be sized generously and spaced at intervals short enough to prevent runoff concentration on fill slopes; and bioengineering measures—vetiver grass hedgerows, live staking, and brush layering—should be applied within the 50-m influence zone to rebuild root-reinforced cohesion over time^[17]. Future research should incorporate time-series monitoring of pore-water pressures and slope displacement to capture the temporal dynamics of destabilisation during monsoon events and to evaluate the effectiveness of remediation measures after installation.

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Contributions Not Qualifying for Authorship

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