



Outcrop-Scale Investigation of Geological and Soil Physical Controls on Slope Stability in the Semilir Formation

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ABSTRACT

Landslides are a major hazard in Indonesia's volcanic terrains, where highly weathered pyroclastic rocks and intense rainfall frequently trigger slope failures. This study aims to identify geological, geomorphological, and soil physical factors controlling slope stability within the Semilir Formation of Gunungkidul, Yogyakarta. Field observations and laboratory analyses were conducted to compare outcrops affected by translational landslides with adjacent stable slopes. Key parameters include bedding orientation, soil bulk density, plasticity index, and water retention capacity. The results indicate that dip-slope bedding orientations strongly predispose slopes to translational failure, whereas counter-dip structures enhance stability. Landslide-prone slopes exhibit higher bulk density, lower plasticity, and reduced water-holding capacity, which accelerate saturation and decrease cohesion during intense rainfall. In contrast, stable slopes possess higher plasticity and greater water retention, often reinforced by vegetation roots. These findings highlight the combined role of geological structure and soil properties as reliable indicators of landslide susceptibility. The study's novelty lies in its outcrop-scale comparative approach within a single volcanic formation, providing practical implications for slope management through vegetation reinforcement, improved drainage, and locally calibrated rainfall thresholds.

Keywords: Semilir Formation, slope stability, soil physical properties, volcanic landscape

INTRODUCTION

Landslides are among the most serious geological hazards in tropical and subtropical regions, particularly within volcanic landscape (Amarasinghe *et al.*, 2024; Arango-Carmona *et al.*, 2025). In Indonesia, volcanic slopes are highly susceptible to failure due to the weak and easily weathered nature of pyroclastic rocks combined with high annual rainfall (Krishna *et al.*, 2016; Muntohar *et al.*, 2022). Even within the same rock formation and under similar climatic conditions, one slope may remain stable while another undergoes translational sliding. In the Semilir Formation of Gedangsari, Gunungkidul Regency, subtle variations in geological structure (bedding orientation, rock type, slope inclination) or soil physical properties (particle density, texture, permeability, plasticity index, maximum water content) can determine whether a slope fails during intense rainfall events.

Recent studies have emphasized the critical role of bedding orientation and geological structure in controlling slope stability. Field observations and numerical simulations in loess areas have shown that slopes with bedding dipping in the same direction as the slope surface (dip-slope) are more prone to translational failures compared to counter-dip slopes (Zhuang *et al.*, 2024). Rainwater infiltration along bedding planes increases localized pore-water pressure and reduces effective stress, thereby triggering slope failure under heavy rainfall conditions. A study focusing on bedding planes parallel to the slope in China corroborates this, showing that undisturbed slip-zone soils suffer sharp degradation in shear strength within the first hour after saturation when bedding is aligned with slope dip (Wu *et al.*, 2024).

In addition, the interaction between soil texture, plasticity, and hydro-mechanical behavior dur-

ing saturation has been highlighted in laboratory and modeling found that soils with low plasticity and limited active clay content exhibited a more significant reduction in cohesion when saturated, especially in subsoil horizons (Jia *et al.*, 2024). This finding underscores that soil water retention capacity and plasticity are critical indicators for predicting slope stability to intense rainfall. Further supporting this, suction monitoring of volcanic residual soils during wet seasons in Yogyakarta shows that decreases in matric suction and increases in moisture content correspond directly with rainfall intensity peaks, leading to reductions in factor of safety (Muntohar *et al.*, 2022).

Despite these advances, a research gap remains in localized, outcrop-scale comparative studies that directly assess why one slope within the same lithostratigraphic unit fails while another remains stable. Such studies are essential to disentangle the relative influences of bedding orientation, weak rock layers, and soil properties on slope stability. Most existing research has focused on regional susceptibility mapping or numerical modeling without field-based comparison of stable and unstable slopes under similar geological and climatic settings.

This study specifically aims to answer three key questions; (1) which geological and structural factors differentiate stable slopes from those affected by translational landslides in the Semilir Formation, (2) how soil physical properties influence slope stability under high-intensity rainfall, and (3) whether these parameters can serve as predictive indicators of landslide susceptibility in volcanic terrains. To address these questions, the research systematically analyzes the geological, geomorphological, and soil physical contrasts between stable and landslide-affected slopes within the Semilir Formation, while evaluating the dominant factors that trigger translational sliding. The novelty of this study lies in its direct, outcrop-scale comparative approach within a volcanic formation. This integrated approach enables the identification of highly localized but practically relevant stability factors, thereby supporting more targeted landslide mitigation strategies in volcanic terrains of Indonesia.

MATERIALS AND METHODS

Study area

The study area is situated in Gedangsari Sub-district, Gunungkidul Regency, Special Region of Yogyakarta, Indonesia, within the Watugede Sub-watershed (Figure 1). This region lies within the Southern Mountain Zone of Java, a geomorphologically complex area shaped by compressional

tectonics and ancient volcanosedimentary deposits. The topography is dominated by volcanic hills, characterized by undulating to steep slopes. The main river flows through the Semilir Formation and plays a significant role in geomorphological processes, particularly by eroding slope toes and triggering slope instability.

This study focused on two adjacent slopes composed of pyroclastic rocks of the Early Miocene Semilir Formation (Surono, 2009), consisting of tuff, lapilli, and tuffaceous sandstone. Geographically, the first slope, which has experienced a translational landslide, is located at 7°50'28.6" S, 110°35'47.1" E, while the second, stable slope is located at 7°50'40.5" S, 110°35'38.7" E. The area is drained by a dendritic river network that contributes to slope erosion. Regarding land use, most of the study area is utilized for agriculture, mixed gardens, and residential yards. Human activities, including land clearing on steep slopes and settlement development near slope areas, further increase the potential risk of landslide-related hazards.

Data collection and analyses

Geological data and soil physical properties were collected from two slope conditions: a previously failed slope and a stable slope. Field measurements systematically included solum depth, surface cracks, landslide type, erosion condition, land cover, and vegetation type. Geological structures, such as bedding strike and dip, slope orientation, and slope gradient, were measured at representative outcrops. In addition, macroscopic rock descriptions, including color, texture, structure, and the presence of fragments, were documented following standard field procedures.

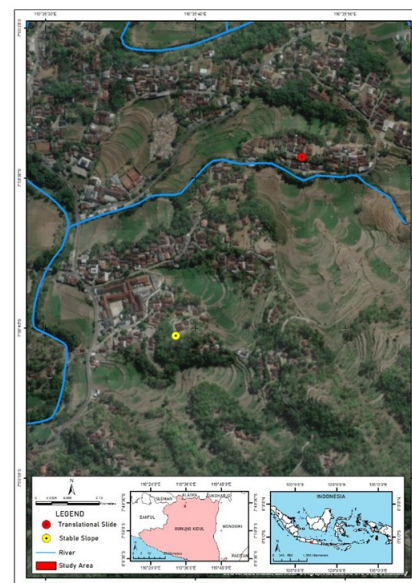


Figure 1. Map of study area and sampling point

Soil samples were collected using purposive sampling with three replications, which were subsequently composited (Soil Survey Division Staff, 2017). Undisturbed soil samples were obtained using a core sampler for the analysis of soil permeability (Irawan *et al.*, 2022). Disturbed soil samples were collected at depths of 0–30 cm and 30–60 cm for laboratory analyses, including: (a) soil texture determined by the pipette method (Irawan *et al.*, 2022); (b) particle density measured using the pycnometer method (Irawan *et al.*, 2022); (c) soil moisture content assessed by the gravimetric method (Irawan *et al.*, 2022); and (d) plasticity index calculated by the Casagrande method as the difference between the liquid limit and the plastic limit (Irawan *et al.*, 2022).

Rainfall data from 2013–2024 were obtained from the Badan Meteorologi, Klimatologi, dan Geofisika Kantor Wilayah Yogyakarta. River network data were sourced from the 2024 Indonesian Topographic Map, while satellite imagery was processed using ArcMap 10.8 Basemap for geomorphological interpretation. Data analysis was conducted integratively by combining field observations, laboratory analyses, and secondary data. Geological and geomorphological characteristics were compared between failed and stable slopes to assess the effects of bedding orientation and toe erosion. Soil physical properties were described to evaluate variations in shear strength and water retention capacity under different slope conditions. All results were synthesized descriptively to identify the dominant factors influencing slope instability in the Semilir Formation, especially within the Gedangsari District.

RESULTS AND DISCUSSION

Geology characteristics

Geological analysis was conducted at two contrasting outcrop locations within the Semilir Formation. Location 1 (7°50'40.5" S, 110°35'38.7" E) exhibits a stable slope, whereas Location 2 (7°50'28.6" S, 110°35'47.1" E) corresponds to a slope that has experienced a translational landslide. Although both locations are situated at the same elevation, they display significant differences in geological characteristics and slope stability responses. At Location 1, interbedded coarse tuff and fine tuff were observed (Figure 2).

The fine tuff has a grain size ranging from 0.004 to 0.06 mm, with good sorting, a closed packing texture, and is composed of silt-sized material. The coarse tuff is whitish-brown in color, with a grain size of 0.25 to 0.5 mm, good sorting, closed packing, and composed of lithic fragments as well

as plagioclase and quartz minerals. The bedding orientation shows a strike of N 92° E with a dip of 35°. In contrast, the slope face of the outcrop is oriented at N 250° E with a dip of 70°. The difference of 158° between the bedding strike and slope strike indicates that the dip direction of the bedding is opposite to the slope inclination (Figure 3). This condition implies relatively higher slope stability, as the bedding dip direction counteracts potential mass movement of soil and rock.

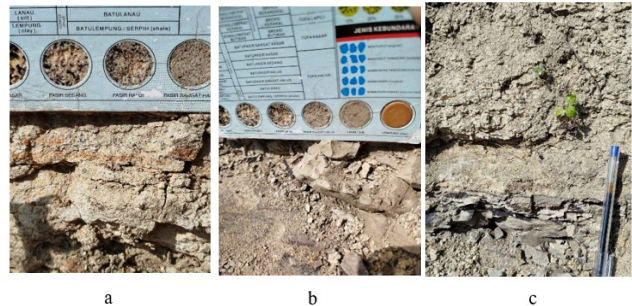


Figure 2. (a) tuffaceous sandstone, (b) fine tuff, (c) interbedded coarse tuff and fine tuff

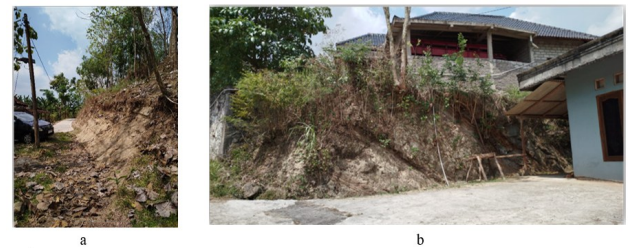


Figure 3. (a) dip of the bedding plane opposite the slope of the front slope of the outcrop

At Location 2, three types of rocks were identified, namely interbedded fine tuff and coarse tuff overlain by lapilli (Figure 4). The lapilli is whitish-brown in color, massive in structure, poorly sorted, open-packed, and composed of rock fragments, volcanic ash, and pumice clasts larger than 2 mm. The fine tuff in this location shows similar characteristics to that observed at Location 1, while the coarse tuff also exhibits comparable color, grain size, and mineral composition. The bedding orientation of the interbedded fine tuff and coarse tuff indicates a strike of N 75° E with a dip of 36°. In contrast, the slope face of the outcrop is oriented at N 89° E with a dip of 80°. The 14° difference between the bedding strike and slope orientation suggests that the bedding dip is aligned with the slope inclination (Figure 5). This condition indicates higher susceptibility to failure, as the massive structure, open packing, and poor sorting of the lapilli

weaken local cohesion, promote crack propagation, and the bedding orientation facilitates downslope mass movement. Additionally, the lateral slope of the outcrop shows an orientation of N 190° E with a dip of 60°, which may act as an additional potential failure plane.

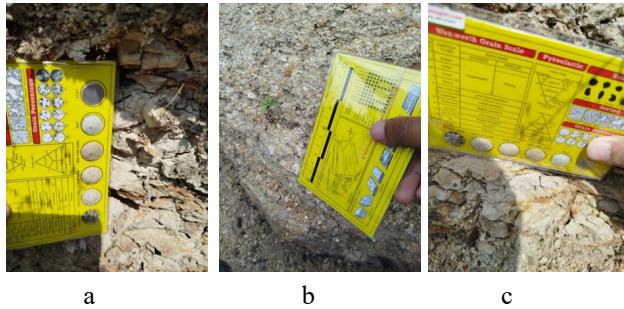


Figure 4. (a) fine tuff, (b) lapilli stone, (c) coarse tuff

This finding demonstrates that geological variability can exert a strong control on landslide susceptibility, even within the same rock formation. Minor variations in rock properties may determine the type of failure and the location of weak zones within a slope, despite being part of the same lithostratigraphic unit (LaHusen & Grant, 2024). Furthermore, studies on anti-dip bedding rock slopes provide insight that counter-dip conditions tend to slow down deformation and reduce progressive failure compared to dip-slope conditions. Slopes with both dip and counter-dip orientations highlight the contrasting dynamic responses in relation to slope stability (Xin *et al.*, 2024).

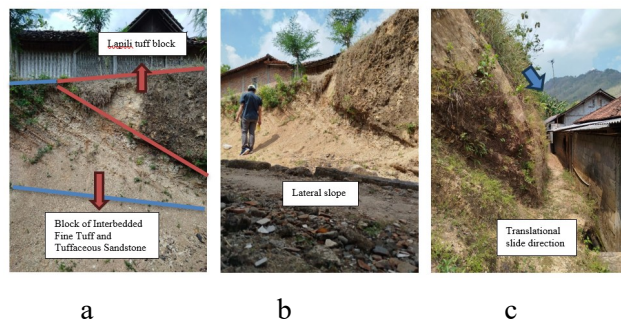


Figure 5. Dip of the bedding plane in the same direction as the slope of the front slope where translational sliding occurs

Geomorphological factors

Understanding the geomorphological and geological settings is essential for interpreting the mechanisms that control slope stability in the study area. Both locations examined in this study are situated

within a volcanic denudational hill zone developed from pyroclastic deposits of the Semilir Formation. A Miocene-aged stratigraphic unit composed predominantly of fine-to coarse-grained volcanoclastic materials. The landscape is characterized by steep slopes, narrow valleys, and deeply eroded outcrops of tuff, tuffaceous sandstone, and intercalated lapilli tuff. These layered deposits, which commonly exhibit bedding dips between 18° and 35°, reflect their origin from explosive volcanic events, as indicated by their grain-size variability, the presence of pumice fragments, and the alternation between massive and laminated tuffaceous units.

The lithologies in this formation are mechanically weak due to their high porosity, low cementation, and advanced weathering grade, which reduce material strength and enhance susceptibility to slope failure. Petrographic and field observations from previous studies indicate that Semilir tuff typically exhibits low uniaxial compressive strength and pervasive alteration of volcanic glass into clay minerals, both of which contribute to reduced durability and cohesion in weathered profiles (Busthan *et al.*, 2024; Muntohar *et al.*, 2022). Although volcanic activity responsible for the deposition of the Semilir Formation ceased during the Late Miocene, its structural legacy continues to exert a strong influence on current slope morphology. The region is tectonically and volcanically dormant today. However, the stratified volcanic deposits remain a fundamental control on slope behavior, particularly where bedding planes dip in the same direction as the slope surface (dip-slope).

Exogenous processes, in contrast, are highly active and strongly shape present-day geomorphodynamics. The area receives an annual rainfall of 2,164 mm/year under a monsoonal regime, producing pronounced wet-dry seasonality that governs hydromechanical and physico-chemical responses of the soil (Figure 6). During the early rainy season, rapid saturation often triggers recurrent slope failures. Additionally, crack-saturation cycles during transitional periods weaken soil aggregates by reducing matric suction, enhancing dispersion of fine particles. It facilitating the development of subsurface slip zones, effects that are particularly evident on dip-slopes such as at Location 2. High rainfall also accelerates both chemical and physical weathering of fine-grained tuff layers, promoting mineral alteration, decreasing cohesion, and increasing the likelihood of slip-surface formation (Busthan *et al.*, 2024; Kumala Sari & Wardani, 2024; Muntohar *et al.*, 2022).

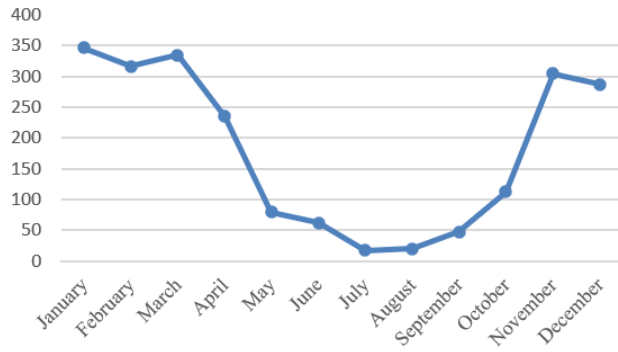


Figure 6. Average monthly rainfall in Gunungkidul Regency

In addition to the influence of rainfall intensity and seasonal variation, the surface hydrological system exerts a critical control on landform evolution and slope stability. Overland flow and subsurface seepage in layered volcanic slopes are governed by the orientation of bedding planes relative to slope inclination. On dip-slopes, rainfall readily infiltrates and migrates along bedding interfaces, where permeability anisotropy promotes the formation of preferential flow paths. This process leads to localized water accumulation, increased pore-water pressure, and a consequent reduction in effective normal stress and interlayer friction, consistent with Terzaghi's principle of effective stress. As a results, both effective cohesion and shear strength decline, favoring the development of planar or translational failures along bedding-parallel surfaces (Zhou *et al.*, 2021).

The interplay between structurally weak lithologies inherited from endogenous volcanic processes and the prevailing exogenous forces—such as intense rainfall, surface erosion, and frequent landslides—produces a geomorphic system of high dynamism. Although tectonic and volcanic activity has largely ceased, rendering the region relatively stable endogenously, the dominance of exogenous drivers makes the Semilir Formation highly vulnerable to land degradation and slope instability. Understanding this multi-scale interaction between endogenous inheritance and exogenous forcing is fundamental to explaining both the long-term evolution of the volcanic landscape and the recurrent landslide mechanism observed in the study area (Cynthia, 2024; Ehsan *et al.*, 2025; He *et al.*, 2025).

Soil physical properties and their influence on slope stability

The comparison of soil physical characteristics between slopes affected by translational slides and stable slopes demonstrates a strong linkage between

soil structure and slope stability (Table 1). The upper soil layer (0–30 cm) at the landslide site exhibits an average bulk density of 2.03 g cm^{-3} with a silty clay texture, indicating a dense structure with limited macroporosity. Such conditions restrict water storage capacity but may allow rapid infiltration through preferential pathways. The maximum water content, reaching only 75.13%, suggests low water retention potential. Under high rainfall, this layer becomes saturated quickly, leading to increased pore-water pressure, reduced effective stress, and a consequent decline in shear strength (Cho *et al.*, 2024; Huang *et al.*, 2023; Leonarduzzi *et al.*, 2021). In contrast, the upper layer of the stable slope exhibits a lower bulk density (1.82 g cm^{-3}) and a clay loam texture, allowing greater water retention as reflected in a higher maximum water content (107.57%). Its higher plasticity index (22.68) indicates greater flexibility to accommodate moisture fluctuations without structural degradation, thereby maintaining mechanical stability during heavy rainfall.

Differences are more pronounced in the lower layer (30–60 cm). On the landslide slope, bulk density increases to 2.05 g cm^{-3} while the texture remains fine, yet maximum water content (74.73%) and plasticity index are both low. This layer, therefore, exhibits limited shear resistance under rising pore-water pressures and acts as a potential slip surface when percolating water from above accumulates (Lira *et al.*, 2024; Pelascini *et al.*, 2022; Song *et al.*, 2024). Conversely, on the stable slope, the lower layer shows lower density (1.90 g cm^{-3}), a clay loam texture, higher water content (108.33%), and a greater plasticity index (27.3), conferring enhanced deformation resistance. Deep-rooted teak vegetation further contributes by reinforcing the soil matrix, reducing infiltration, and increasing slope stability (Fata *et al.*, 2023; Spiekermann *et al.*, 2021). Overall, the observed contrast in soil physical parameters indicates that soil density, texture, and plasticity collectively determine the hydromechanical response of slopes and thus govern their stability within the Semilir Formation.

The key differences between stable and landslide slopes lie in maximum water-holding capacity and soil plasticity. Landslide slopes are characterized by low water retention and plasticity, making them more susceptible to weakening when saturated. In contrast, stable slopes exhibit soils with high water-holding capacity, high plasticity, and reinforcement by deep-rooted woody vegetation, thereby providing greater resistance against the effects of intensive infiltration. These variations in soil physical properties explain why, under similar geological and rainfall conditions, one slope may fail by translational sliding while another remains stable.

Tabel 1. Soil physics properties

Location	Soil depth (cm)	Parameter							
		Particle density (g cm ⁻³)	Texture	Permeability (cm s ⁻¹)	Permeability class	Soil moisture	Maximum water content	Plasticity index	Degree of expansive
Location 1 (Translational Slide)	0-30	2.44	Clay Loam	18.30	High	7.77	75.13	17.21	Moderate
	30-60	2.05	Silty Clay	14.17	High	8.26	74.73	11.26	Moderate
Location 2 (Stable)	0-30	1.82	Clay Loam	16.16	High	13.47	107.57	22.68	High
	30-60	1.90	Clay Loam	13.21	High	11.85	108.33	27.30	High

Source: Analysis data (2025)

Implication for landslide hazard mitigation

Deep-rooted woody vegetation provides two crucial contributions to slope stability. Mechanically, large roots increase effective cohesion in both surface and subsurface zones, thereby slowing crack propagation and soil movement (Fata *et al.*, 2023; Masi *et al.*, 2021). Hydrologically, roots absorb water, reduce pore-water pressure, and delay saturation during high or prolonged rainfall events (Demir *et al.*, 2024). Recent empirical evidence and modeling demonstrate that the reinforcing effect of roots is strongly dependent on effective rooting depth and root density. Woody trees contribute root cohesion that can significantly increase slope safety factors when roots penetrate potential slip surfaces (Marzini *et al.*, 2023).

Surface and subsurface drainage management represents an efficient technical intervention to reduce landslide risk on dip-slopes and can be implemented through: (a) the construction of surface channels, (b) the development of lateral drains along contours, and (c) the installation of subsurface drains in critical zones (Tang *et al.*, 2024; Zhang *et al.*, 2023). These measures can prevent preferential seepage along bedding planes and reduce pore-water pressure rise during extreme rainfall. Both simulation studies and field applications confirm that the combination of bio-engineering measures and drainage improvements exerts a substantial influence on slope safety factors (Chen *et al.*, 2023).

Rainfall-threshold-based early warning systems represent another practical tool that can be recommended. Cumulative daily thresholds or locally adjusted intensity thresholds enable authorities to issue alerts before soil saturation reaches critical levels (Millán-Arancibia & Lavado-Casimiro, 2023; Salee *et al.*, 2022). Recent studies on rainfall thresholds indicate that accurate determination of thresholds should integrate historical rainfall records, antecedent soil moisture conditions, and local geological characteristics. This approach can be applied in priority

mitigation areas, for example, dip-slopes with sensitive subsoils allowing for faster identification and improved community preparedness (Peng & Wu, 2024).

Disaster mitigation should be designed as an integrated approach that combines vegetative conservation (revegetation or the planting of deep-rooted trees accompanied by ground cover vegetation) (Lovita & Sulistyono, 2025; Marzini *et al.*, 2023; Pisano & Cardile, 2023), technical conservation such as surface drainage engineering (Kumala Sari & Wardani, 2024; Sari *et al.*, 2023), and hazard mapping based on rainfall thresholds for early warning (Chen *et al.*, 2023). This integrated strategy not only reduces the probability of slope failure during peak rainy seasons (January to March) but also enhances long-term landscape resilience against weathering and erosion in the pyroclastic deposits of the Semilir Formation. The practical implication of this study is to recommend prioritizing interventions on layered dip-slopes and protecting hydro-critical zones (30–60 cm) that show potential as slip surfaces.

CONCLUSION

This study demonstrates that slope stability within the volcanic terrain of the Semilir Formation is primarily governed by the interaction between geological structures and soil physical properties. Comparative analysis between stable and landslide-affected slopes reveals that bedding orientation is a critical geological control. Slopes where bedding planes dip parallel to the slope surface are significantly more susceptible to translational failure, whereas counter-dip bedding offers greater resistance to mass movement. Soil physical properties further explain contrasting slope stability under high-intensity rainfall. Slopes with higher bulk density, lower water retention capacity, and low plasticity index are more prone to rapid saturation and loss of cohesion, leading to translational sliding. In contrast, soils with higher plasticity and greater maximum water content, par-

ticularly when reinforced by deep-rooted vegetation, are better able to maintain stability even under extreme rainfall. These findings confirm that geological structure and soil physical parameters can serve as predictive indicators for landslide susceptibility in volcanic terrains. Outcrop-scale comparative analysis, as applied in this research, highlights the importance of localized assessments in complementing regional-scale hazard mapping. From a practical perspective, slope stabilization in the Semilir Formation should prioritize integrated measures: promoting deep-rooted vegetation to increase root cohesion, improving drainage systems to reduce pore-water pressure along bedding planes, and applying locally calibrated rainfall thresholds for early warning. Such interventions, particularly on dip-slope conditions and sensitive subsurface layers (30–60 cm), are essential for reducing landslide risk and enhancing long-term landscape resilience.

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