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Geological Controls on Soil Shear Strength and Slope Instability in the Watugede Sub-Watershed

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Abstract

Landslides are a common geomorphological hazard in tropical volcanic regions, particularly in areas with steep slopes and complex geological settings. Variations in soil properties on soil shear strength across different geological formations. This study investigated the physical and mechanical properties of soils developed from the Kebobutak, Semilir, and Nglanggeran Formations and evaluated their relationship with landslide susceptibility in the Watugede Sub-Watershed. Field surveys, geological observations, and soil sampling were conducted at landslide and non-landslide sites. Soil samples were collected from two depth intervals (0-30 cm and 30-60 cm) and analyzed for soil texture, maximum water content, plasticity index, clay sensitivity, cohesion, internal friction angle, and soil shear strength. A descriptive-comparative analysis was applied to assess differences among geological formations and slope conditions. The results indicate that landslide areas generally have higher moisture content and plasticity, accompanied by lower cohesion, internal friction angle, and shear strength than non-landslide areas. Soils derived from the Semilir Formation exhibited the greatest susceptibility to landslides due to their high water-retention capacity and relatively low shear resistance, whereas soils developed on the Nglanggeran Formation showed higher shear strength and greater slope stability. These findings demonstrate that geological formations play a significant role in controlling soil mechanical behavior and slope instability through their influence on soil physical and mechanical properties. The results provide a scientific basis for landslide susceptibility assessment, slope stability modeling, hazard mitigation strategies, and land-use planning in volcanic landscapes.

1. Introduction

Landslides and slope instability are major environmental and geohazard concerns in many regions, particularly in areas with complex geological settings and intensive land use (Alcántara-Ayala, 2025; Appukuttan et al., 2025; Di Maio et al., 2024; Kinde et al., 2024; Liu et al., 2024; Wang et al., 2024). In tropical regions such as Indonesia, the interaction between high rainfall intensity and steep topography frequently triggers slope failures (Arrisaldi et al., 2021; Indratmoko and Koestoer, 2025; Sarah et al., 2024), resulting in loss of life (Wilopo and Fathani, 2021), infrastructure damage, and land degradation (Delorme et al., 2017; Stock et al., 2016). These conditions highlight the importance of understanding the fundamental factors that control slope stability to support effective disaster mitigation and sustainable land management. Understanding the factors that control slope stability is therefore essential for improving landslide mitigation strategies and supporting sustainable land management in vulnerable landscapes.

From a geotechnical perspective, slope stability is primarily governed by the mechanical properties of soil, particularly shear strength parameters such as cohesion (c) and internal friction angle (φ) (Azarafza et al., 2022; Harabinova et al., 2026). These parameters describe the soil's resistance to shear stress and play a critical role in determining the slope failure mechanism (Khan and Wang, 2021; Li and Cai, 2020). Variations in soil shear strength directly influence slope stability, especially under triggering factors such as rainfall infiltration, changes in pore water pressure, or seismic activity (Kang et al., 2022; Prasetyaningtiyas et al., 2023; Zhang et al., 2025). A reduction in cohesion or internal friction angle decreases the shear resistance of soil, thereby increasing the likelihood of slope failure under unfavorable hydrological conditions (Espinosa Fuentes and El Naggar, 2025; Ullah, 2021).

Soil mechanical and physical properties are closely related to soil genesis processes, which are strongly influenced by the characteristics of the parent material (Alnaimy et al., 2023; Wilson, 2019). Geological formations affect soil development through differences in mineral composition, lithology, and weathering intensity, resulting in variations in texture, structure, clay mineralogy, and bonding mechanisms (Deng et al., 2025; Rahayu et al., 2023). Variations in these factors influence particle-size distribution, clay mineral formation, aggregate development, and soil structure, which subsequently affect water retention capacity, plasticity index, bonding mechanisms, and shear strength characteristics (Baldermann et al., 2021; Swart and Dippenaar, 2025). Consequently, soils derived from different geological formations may exhibit contrasting values of cohesion and internal friction angle, even when developed under similar climatic and topographic conditions. Understanding this relationship is particularly important in volcanic terrains, where contrasting lithological units may produce substantially different soil behaviors despite experiencing similar climatic and topographic conditions.

Volcanic landscapes provide suitable environments for investigating these relationships because they commonly exhibit high lithological variability, intensive weathering processes, and frequent landslide occurrences (Cahyadhi et al., 2025; Rodríguez and Román, 2026). The Watugede Sub-Watershed, located in the upper part of the Oyo River Basin, Special Region of Yogyakarta, Indonesia, represents a typical tropical volcanic landscape characterized by steep slopes and recurrent slope instability. The watershed comprises three contrasting volcanic formations: Kebobutak, Semilir, and Nglanggeran. These formations differ in lithological composition, weathering characteristics, and geomorphology. The Semilir Formation is composed predominantly of fine pyroclastic deposits, whereas the Kebobutak and Nglanggeran Formations are characterized by volcanic breccias with varying degrees of weathering and consolidation. Such lithological contrasts are expected to influence soil genesis and subsequently produce variations in soil physical and mechanical properties associated with slope stability.

Previous studies on slope stability and landslide susceptibility largely focused on topographic attributes, rainfall characteristics, land use changes, and hydrological processes (Arrisaldi et al., 2021; Cordoba et al., 2020; Liu et al., 2024). Although these studies have substantially improved the understanding of landslide triggering mechanisms and susceptibility patterns, comparatively less attention has been given to the role of geological formations in controlling soil mechanical behavior. Despite numerous investigations of landslide-prone areas in Indonesia, information regarding the comparative shear strength characteristics of soils developed from different volcanic formations remains limited. In particular, comparative evaluations of soil cohesion and internal friction angle across the Kebobutak, Semilir, and Nglanggeran Formations have not been comprehensively conducted within the Watugede Sub-Watershed. The mechanisms linking geological formation, soil properties, and landslide occurrence remain poorly documented, particularly in tropical volcanic landscapes.

This study addresses these knowledge gaps by integrating geological characterization with analyses of soil physical and mechanical properties across contrasting volcanic formations under landslide and non-landslide conditions. Unlike previous studies that primarily emphasized external triggering factors such as rainfall, topography, and land use. This research focuses on the geological controls governing soil physical and mechanical behavior and their implications for slope instability. The novelty of this study lies in the comparative evaluation of soil shear strength parameters across three volcanic formations while simultaneously examining differences between landslide and non-landslide sites. Such an approach provides a more comprehensive understanding of how geological variability influences soil characteristics, shear resistance, and landslide occurrence within tropical volcanic landscapes.

Therefore, this study aims to analyze the variation of soil shear strength parameters across three geological formations and to evaluate their relationships with soil physical properties and geological characteristics to support landslide susceptibility assessment and sustainable land management. The results are expected to improve understanding of geological controls on soil physical and mechanical behavior and provide a scientific basis for landslide susceptibility assessment, slope management, and disaster mitigation in volcanic environments.

2. Research Methods

2.1. Research Location

This research was conducted in the Watugede Sub-Watershed, which is part of the main river network of the Oyo River Basin. The study area is geographically located between approximately 7°49'30"–7°53'0" South Latitude and 110°34'0"–110°38'0" East Longitude (Figure 1). Administratively, the research site is located in Gunungkidul Regency, Special Region of Yogyakarta, Indonesia. The Watugede Sub-Watershed represents an upstream catchment characterized by hilly to undulating terrain with locally steep slopes. Elevation varies from valley bottoms to structural hill ridges typical of the southern Java physiographic zone. The region experiences a tropical monsoonal climate with distinct wet and dry seasons. High rainfall intensity during the wet season enhances weathering processes and increases the potential for slope instability, particularly on steep slopes.

Geologically, the study area comprises three distinct formations distributed within the sub-watershed. These formations exhibit contrasting lithological compositions, structural characteristics, and weathering responses. Such geological variability influences soil formation processes, resulting in differences in soil physical and mechanical properties. These variations provide an appropriate basis for evaluating the influence of geological formations on soil shear strength parameters.

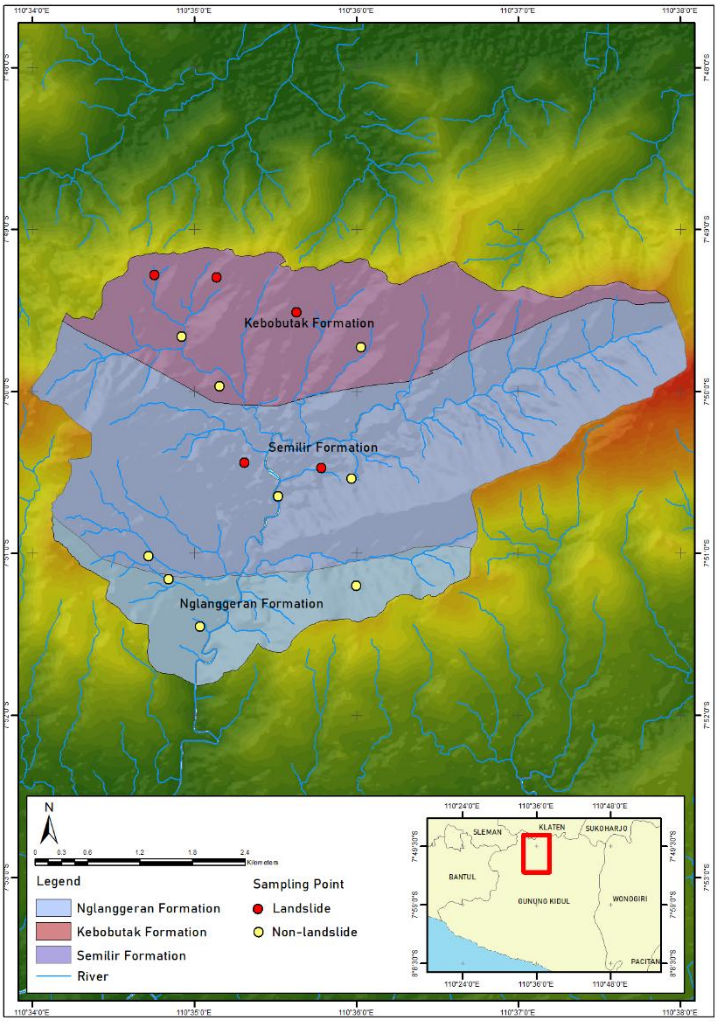


Figure 1. Study area and distribution of landslide and non-landslide sampling points across three geological formations (Kebobutak, Semilir, and Nglanggeran) in the Watugede Sub-Watershed, Gunungkidul Regency, Indonesia.

This study employed a combination of field investigation and laboratory experimental analysis. Fieldwork included geological observation, slope characterization, and soil sampling from representative locations within each formation. Sampling sites were selected to represent both landslide-affected areas and adjacent non-landslide areas to enable comparative analysis of soil mechanical behavior under different slope stability conditions.

Laboratory testing was subsequently conducted to determine soil physical properties and shear strength parameters, allowing systematic assessment of the relationship between geological formation, slope condition, and soil mechanical behavior. The overall research workflow adopted in this study is summarized in Figure 2, which illustrates the sequential steps from field investigation to data analysis and interpretation.

2.2. Research Implementation

2.2.1. Field Survey

Field surveys were conducted as the initial stage of the research to obtain an overview of geological, geomorphological, and slope conditions within the Watugede Sub-Watershed.The survey aimed to identify representative sampling locations and to observe field evidence of slope instability. Observations included slope morphology, lithological outcrops, and indications of previous landslide activity such as scarps, displaced materials, and disturbed vegetation patterns. The field survey also served to determine representative sites within the Kebobutak, Semilir, and Nglanggeran Formations.

2.2.2. Rock Description Method

Rock characterization at the research site was conducted using the macroscopic rock description method to identify the lithological characteristics of the Kebobutak, Semilir, and Nglanggeran Formations. This direct observation technique relies on visual examination of rock samples without the use of a microscope to determine observable physical properties. observed parameters included rock color, structure, grain size, grain shape, sorting, packing, and mineral composition that could be recognized visually. fractures, cavities, or weathering features were also recorded. This method allows preliminary classification of rock types and provides important information on lithological characteristics that influence soil formation and slope stability.
Several instruments were used during macroscopic rock description, including a geological hammer for collecting rock samples, a hand lens for observing mineral and grain characteristics, a rock comparator for lithological identification, and a hydrochloric acid (HCl) solution to detect the presence of carbonate minerals. The macroscopic observations were supported by regional geological information from the Wonosari Sheet Geological Map (Surono, 2008), which served as a reference for identifying geological formations in the study area.

2.2.3. Identification of Landslide and Non-Landslide Areas

Identification of landslide and non-landslide areas was conducted through detailed field observations supported by geomorphological interpretation, secondary landslide records, and local community information. Landslide sites were selected based on the presence of clear morphological indicators, including head scarps, displaced soil and rock materials, cracks, hummocky topography, and disturbed vegetation patterns. These indicators provide direct evidence of previous slope failures observed in the field.

To improve the reliability of landslide identification, field observations were complemented by secondary landslide disaster records obtained from the Indonesian National Disaster Management Agency. In addition, interviews and informal discussions with local residents were conducted to gather information regarding past landslide occurrences, frequency of slope failures, and locations known to have experienced landslide activity. The combination of geomorphological evidence, official disaster records, and local knowledge was used to confirm the classification of landslide sites.

Non-landslide sites were selected from adjacent slopes within the same geological formation that exhibited relatively stable conditions and showed no visible evidence of recent or historical landslide activity based on field observations, disaster records, and information obtained from local residents. To minimize the influence of external factors, non-landslide locations were topographic settings and land-use conditions comparable to those of the landslide sites. This classification was used to select representative sampling locations to evaluate differences in soil physical and mechanical properties between unstable and relatively stable slopes across different geological formations.

2.2.4. Soil Sampling

Soil sampling was conducted at representative landslide and non-landslide locations within the Kebobutak, Semilir, and Nglanggeran Formations. A total of 14 sampling points were established across the study area, consisting of three landslide sites and three non-landslide sites in the Kebobutak Formation, two landslide sites and three non-landslide sites in the Semilir Formation, and three non-landslide sites in the Nglanggeran Formation. No landslide sites were identified within the Nglanggeran Formation. At each sampling point, soil samples were collected from two depth intervals: 0-30 cm and 30-60 cm, representing the surface and subsurface soil horizons that may influence slope stability. Consequently, a total of 28 composite soil samples were obtained (14 sampling points x 2 depth intervals).

For each depth interval, soil sampling was repeated three times within the same sampling point to account for local variability. The three subsamples collected at each depth were then combined into a single composite sample representing that sampling point and depth interval. Therefore, the laboratory analyses were performed on 28 composite samples.

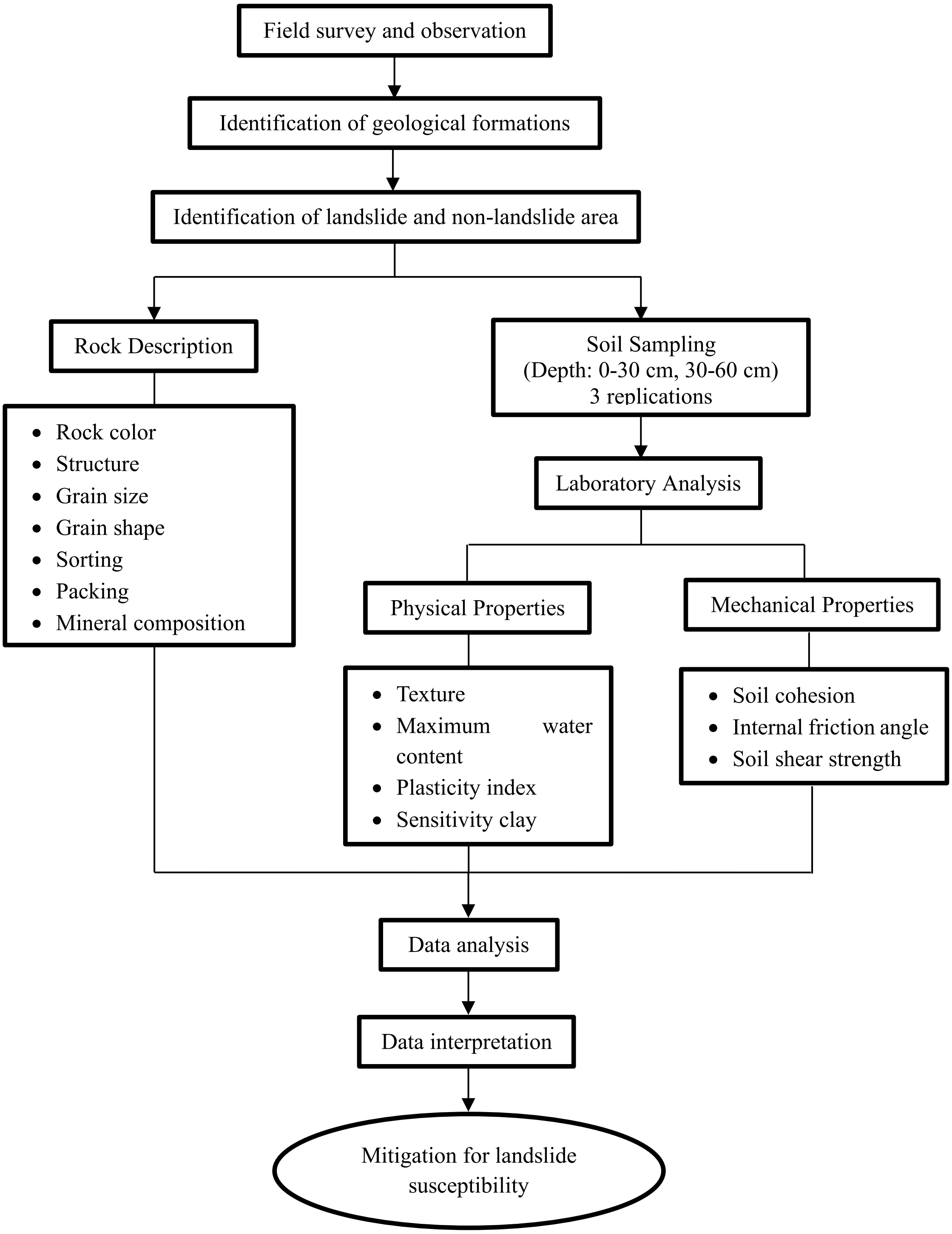


Figure 2. Research workflow for evaluating landslide susceptibility in the Watugede Sub-Watershed.

2.2.5. Laboratory Analysis

Laboratory analyses were conducted to determine both the physical and mechanical properties of the collected soil samples. The physical properties analyzed included soil texture, maximum water content, plasticity index, and clay sensitivity. Soil texture was determined using particle-size distribution analysis to quantify the proportions of sand, silt, and clay fractions. Maximum water content was measured to evaluate soil water-holding capacity. The plasticity index was determined from the Atterberg limits, and clay sensitivity was evaluated to assess the response of clay-rich soils to changes in moisture conditions.

Soil mechanical properties were determined using the Direct Shear Test. The test was conducted under several normal stress levels to establish the relationship between normal stress and shear stress at failure. The resulting failure envelope was interpreted using the Mohr-Coulomb failure criterion. Soil cohesion (c) was obtained from the intercept of the failure envelope, whereas the internal friction angle (φ) was calculated from the slope of the failure envelope. These parameters were subsequently used to evaluate the shear resistance and stability characteristics of soils developed from different geological formations.

2.3. Data Analysis

Data obtained from field observations and laboratory analyses were analyzed using a descriptive-comparative approach. Soil physical and mechanical properties were organized according to geological formation, slope condition (landslide and non-landslide), and soil depth (0-30 cm and 30-60 cm). The results from three replicates at each sampling depth were averaged to obtain representative values for each sampling location. Comparative analyses were conducted to evaluate variations in soil texture, maximum water content, plasticity index, clay sensitivity, soil cohesion, and internal friction angle among geological formations and between landslide and non-landslide sites. The analysis focused on identifying patterns and contrasts in soil behavior associated with different geological settings. Furthermore, the results were integrated with geological and geomorphological information to evaluate the relationships among lithology, soil physical and mechanical properties, and landslide occurrence within the Watugede Sub-Watershed.

3. Results and Discussion

3.1. Geological and Geomorphological Characteristics

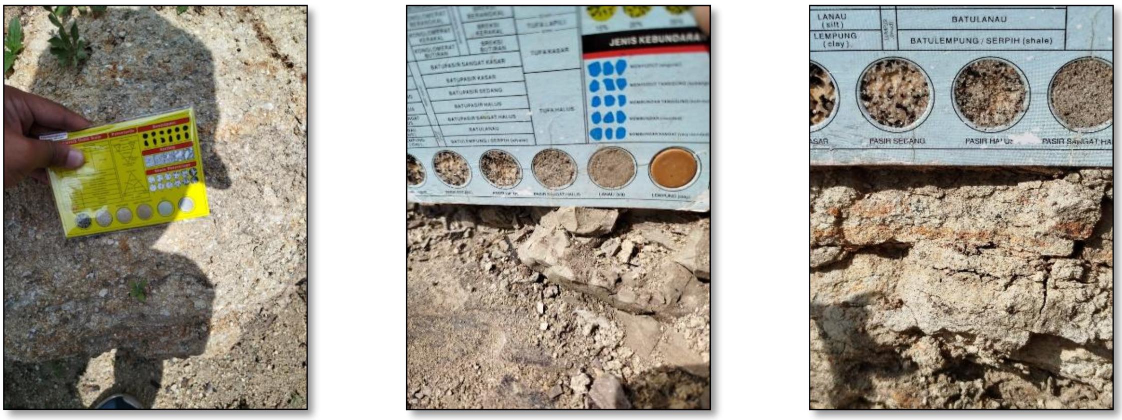
Field observations indicate that the Watugede Sub-Watershed comprises three main volcanic formations: Kebobutak, Semilir, and Nglanggeran. These formations exhibit different lithological compositions and geomorphological characteristics, which influence soil-forming processes and the mechanical behavior of soils developed above them. Lithological observations of the Kebobutak Formation were conducted at a representative outcrop located at coordinates 7°51’36.472” S latitude and 110°35’0.693” E longitude. The outcrop consists of pyroclastic breccia overlain by tuff and lapilli layers in semi-weathered conditions (Figure 3).

(a) (b) (c)

Figure 3. Outcrop of Pyroclastic Breccia (a and b) and Tuff (c) of the Kebobutak Formation.

The presence of coarse volcanic fragments embedded in a finer matrix indicates deposition from volcanic explosive processes (Montanaro et al., 2021; Yao et al., 2025). Geomorphologically, areas dominated by the Kebobutak Formation are characterized by narrow valleys and steep to highly dissected slopes. Such morphological characteristics suggest relatively rapid erosion and weathering, which contribute to the development of thick soil mantles on slopes.

The Semilir Formation was observed at three representative outcrops within the study area. Field observations indicate that this formation is dominated by tuff and lapilli deposits derived from volcanic pyroclastic materials (Figure 4). Compared with the Kebobutak and Nglanggeran Formations, the Semilir Formation consists of relatively finer-grained materials that are more susceptible to weathering. These lithological characteristics promote the development of soils with finer textures and greater water-retention capacity, which may influence soil strength and slope stability (Anda et al., 2023; Indrawan et al., 2024).



(a) (b) (c)

Figure 4. Outcrop of Lapilli (a) and Tuff (b and c) of the Semilir Formation.

The Nglanggeran Formation was observed at two representative outcrops within the study area. Based on field observations, the formation is predominantly composed of pyroclastic breccia (Figure 5), characterized by coarse volcanic fragments embedded within a relatively compact matrix. Compared with the tuff-dominated Semilir Formation, the Nglanggeran Formation exhibits a stronger rock framework and greater resistance to weathering. Geomorphologically, this formation is associated with steep and rugged hills that reflect its relatively resistant lithology. The coarse material composition and stronger rock structure influence the rate of weathering and the characteristics of the soils formed above it, potentially contributing to higher shear resistance compared with soils developed from finer pyroclastic deposits (Indrawan et al., 2006; Larimer et al., 2022).

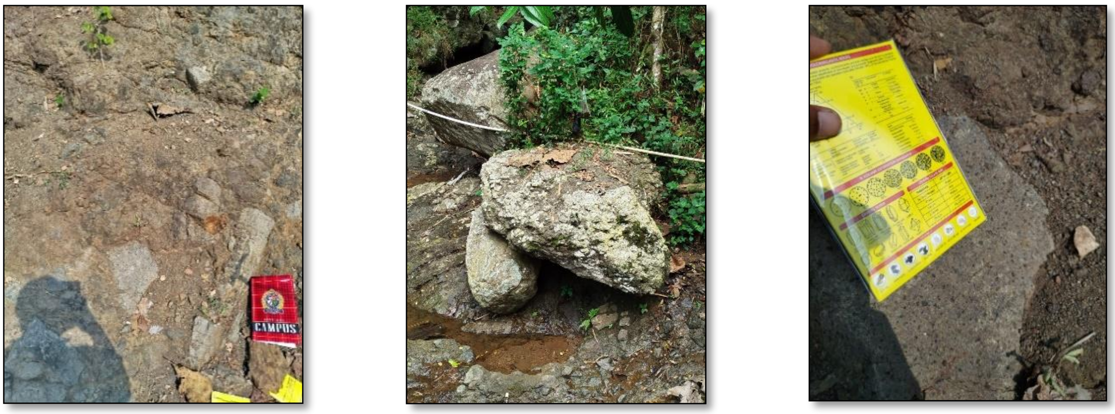


Figure 5. Outcrop of Pyroclastic Breccia of the Nglanggeran Formation.

Overall, the three volcanic formations show significant differences in lithological composition and geomorphological characteristics. These differences play an important role in controlling the weathering processes, soil formation, and the development of soil physical and mechanical properties (Adekiya et al., 2024; D'Addario et al., 2023; Hakim et al., 2024; Lima et al., 2022). These formations exhibit contrasting lithological compositions, mineralogical characteristics, weathering behaviors, and geomorphological settings, all of which exert a fundamental control on soil genesis and the subsequent mechanical behavior of soils developed above them. In volcanic terrains, parent material is one of the primary factors governing pedogenesis because the mineral composition, grain-size distribution, degree of consolidation, and structural fabric of the source rock determine both the rate and pathway of weathering (Santos et al., 2021). As weathering progresses, these lithological characteristics influence the transformation of primary volcanic minerals into secondary clay minerals (Wilson, 2019), the accumulation of fine particles (Indrawan et al., 2024; Kumari and Mohan, 2021), and the development of soil structure (Ahmad et al., 2020; Liu et al., 2026), thereby controlling key physical and mechanical properties relevant to slope stability.

The volcanic formations in the Watugede Sub-Watershed differ markedly in their lithological composition. Tuff-dominated deposits, such as those commonly found within the Semilir Formation, are composed of relatively fine pyroclastic materials that possess high porosity and are generally more susceptible to physical disintegration and chemical alteration. The rapid weathering of these materials promotes the formation of soils enriched in silt and clay fractions, resulting in finer soil textures and greater water-retention capacity (Alghamdi et al., 2023; Yulina et al., 2025). Increased clay content often enhances soil plasticity and moisture sensitivity, particularly under prolonged rainfall conditions (Liu, 2025; Thounaojam and Ibotombi, 2024). As water accumulates within the soil matrix, pore-water pressure may increase while effective stress decreases, reducing the soil's resistance to shear failure (Kang et al., 2022; Luo and Ma, 2024). Consequently, soils derived from highly weathered tuffaceous materials are frequently associated with lower slope stability and greater susceptibility to landslide initiation (Zaenurrohman et al., 2025).

In contrast, volcanic breccias, which dominate the Kebobutak and Nglanggeran Formations, contain coarser volcanic fragments embedded within a matrix of finer materials. The larger grain size and relatively stronger rock framework generally result in slower weathering rates and the production of soils with a higher proportion of coarse particles. Such soils typically exhibit lower plasticity and reduced water-retention capacity compared with soils derived from fine-grained pyroclastic deposits. The presence of coarse fragments can also enhance drainage and reduce the accumulation of excess pore-water pressure during rainfall events (Chen et al., 2021; Qi et al., 2025; Zafra-Mejía et al., 2025). These characteristics may contribute to higher internal friction angles due to increased particle interlocking and frictional resistance, thereby improving the soil's ability to withstand shear stresses on slopes.

The observed lithologic differences among the Kebobutak, Semilir, and Nglanggeran Formations suggest that each may produce distinct soil properties through different weathering pathways. Variations in particle-size distribution, clay development, water-retention characteristics, and soil structure are expected to influence soil mechanical behavior, particularly shear strength parameters related to slope stability. Therefore, evaluating the physical and mechanical properties of soils developed from these formations is essential for understanding the mechanisms controlling landslide occurrence in the Watugede Sub-Watershed. The novelty of this study lies in linking these geological differences directly to soil shear strength characteristics under both landslide and non-landslide conditions.

3.2. Soil Physical and Mechanical Properties and Their Implication for Landslide Occurrence

The differences in lithological composition and geomorphological characteristics among the three formations influence the development of soil physical and mechanical properties, which are closely related to slope stability. Variations in parent material, weathering intensity, and geomorphological processes control the physical characteristics of soils formed above each formation (Chisambi and Shinjo, 2026; Liao et al., 2022). These differences subsequently affect the mechanical behavior of the soils, particularly their shear strength parameters, which play a crucial role in determining slope stability (Espinosa Fuentes and El Naggar, 2025; Tetteh et al., 2025). The results of soil physical and mechanical analyses from different formations, slope conditions, and soil depths are presented in Table 1.

Table 1. Physical and mechanical properties of soils derived from different geological formations under landslide and non-landslide conditions in the Watugede Sub-Watershed

Formation	**Slope Condition**	**Soil Depth (cm)**	**Texture**	**Maximum Water Content (%)**	**Plasticity Index (%)**	**Clay Sensitive**	**Soil Cohesion ($kg\ cm^{-2}$)**	**Internal friction angle (φ)**	**Shear Strength ($kg\ cm^{-2}$)**
Kebobutak	Non-Landslide	0-30	Sandy Clay Loam	74.02	23.57	2.50	0.46	32°	0.569–1.848
		30-60	Sandy Loam	72.26	25.36	2.42			
	Landslide	0-30	Loamy Sand	67.81	19.36	2.51	0.00	28°	0.837–1.690
		30-60	Sandy Loam	52.87	17.86	2.41			
Semilir	Non-Landslide	0-30	Loam	111.97	22.68	2.03	0.45	27°	0.790–1.611
		30-60	Loamy Sand	116.51	27.31	1.71			
	Landslide	0-30	Clay Loam	75.13	11.26	2.04	0.40	20°	0.774–1.753
		30-60	Silty Clay	74.73	17.21	2.14			
Nglanggeran	Non-Landslide	0-30	Loamy Sand	81.09	7.79	2.85	0.45	35°	0.790–1.611
		30-60	Sandy Loam	79.45	8.28	2.84			

The shear strength values in Table 1 represent the range of shear stresses recorded at failure during the Direct Shear Test under different applied normal stress levels. These values correspond to the minimum and maximum failure shear stresses obtained from the test and therefore reflect the mechanical response of the soil under varying loading conditions rather than differences among sampling depths. The resulting shear stress-normal stress relationships were subsequently used to construct the Mohr-Coulomb failure envelope and derive soil cohesion and internal friction angle, which are discussed as the principal indicators of slope stability in this study.

The soils developed on the Kebobutak Formation generally show characteristics associated with the weathering of pyroclastic breccia and volcanic tuff materials. At both sampling depths (0-30 cm and 30-60 cm), the soils tend to exhibit relatively fine textures with considerable proportions of silt and clay fractions. In landslide areas, soil layers commonly exhibit higher moisture content and lower bulk density than at non-landslide sites. Increased soil moisture reduces interparticle friction and weakens soil structure, potentially reducing slope stability. The presence of higher plasticity and clay sensitivity in the landslide locations also indicates a greater susceptibility of the soil structure to deformation when subjected to external stresses or increased pore water pressure (Budianta et al., 2022; Nofrizal et al., 2025; Tchuwa and Makande, 2025; Troncone et al., 2023).

In contrast, soils located in non-landslide areas within the Kebobutak Formation generally display slightly higher shear strength parameters, particularly in terms of cohesion and internal friction angle. These characteristics suggest relatively stronger soil structure and greater resistance to shear deformation. However, the differences between landslide and non-landslide sites are not always substantial, indicating that soils in the non-landslide areas may still possess inherent susceptibility to slope failure under certain triggering conditions, such as prolonged rainfall or increased groundwater infiltration.

Soils developed on the Semilir Formation exhibit somewhat different characteristics due to the dominance of fine-grained pyroclastic materials such as tuff and lapilli. These materials tend to weather into soils with relatively high silt and clay contents, which can significantly influence soil plasticity and water retention capacity (Amiri et al., 2026; Asniar et al., 2019). At landslide locations, the soils generally show higher maximum water content and plasticity index compared to non-landslide areas. Such conditions indicate a higher capacity for water retention and a greater potential for pore water pressure development during rainfall events (Ahmad et al., 2019; Wang et al., 2020). Elevated pore water pressure can significantly reduce effective stress and shear strength, thereby increasing the likelihood of slope failure (Cheng et al., 2024; Espinosa Fuentes and El Naggar, 2025).

From a mechanical perspective, the soils developed on the Semilir Formation generally exhibit lower internal friction angles than those developed on the Kebobutak Formation. Lower friction angles indicate weaker interparticle resistance, which may contribute to slope instability when combined with high moisture conditions (Amalia et al., 2025; Khadka and Kolawole, 2026). In landslide locations, the measured shear strength parameters are typically lower than those in non-landslide areas, suggesting that mechanical soil resistance has already been reduced due to weathering and moisture influence (Bunn et al., 2020; Chen et al., 2026; Kinde et al., 2024).

The soils formed on the Nglanggeran Formation show characteristics influenced by the weathering of volcanic breccia with relatively coarser fragments. Compared to the Semilir Formation, soils derived from the Nglanggeran Formation tend to contain slightly coarser particles and relatively lower plasticity. These conditions may contribute to somewhat higher internal friction angles, indicating greater interparticle resistance (Smith, 2026). However, the steep-slope morphology commonly associated with the Nglanggeran Formation may still increase slope susceptibility to gravitational mass movement despite relatively stronger soil mechanical properties.

Comparison between landslide and non-landslide locations across the three formations indicates that landslide sites are generally characterized by higher soil moisture, higher plasticity, and lower shear strength parameters. These characteristics reduce the soil's resistance to shear stress and increase the likelihood of slope failure. In contrast, non-landslide sites generally exhibit slightly higher cohesion and internal friction angle values, suggesting relatively more stable slope conditions.

Nevertheless, the presence of similar soil characteristics between landslide and non-landslide areas suggests that slopes currently classified as stable may still possess potential susceptibility to landslides in the future. External triggering factors such as intense rainfall, land-use changes, or progressive weathering processes may gradually reduce soil strength and initiate slope failure. Among the three geological formations, the Semilir Formation appears to exhibit relatively higher susceptibility to landslides based on its soil physical and mechanical properties. The dominance of fine-grained pyroclastic materials promotes the development of soils with higher plasticity (Ahmad et al., 2020; Bilotta et al., 2005), greater water retention capacity (Albarki et al., 2025; Anda et al., 2023), and relatively lower shear strength parameters (Elankumaran et al., 2024; Olivares and Picarelli, 2003). These conditions can significantly reduce slope stability, particularly during periods of high rainfall.

Overall, the results indicate that geological formation plays a significant role in controlling soil characteristics and slope stability within the Watugede Sub-Watershed. The interaction among lithological composition, soil physical and mechanical properties determines the vulnerability of slopes to landslides. Therefore, understanding the variability of soil properties derived from different geological formations is essential for improving landslide susceptibility assessment and land management strategies in the study area.

3.3. Implication for Landslide Mitigation

The findings of this study provide important implications for landslide mitigation strategies in the Watugede Sub-Watershed. The observed differences in soil physical and mechanical properties among geological formations indicate that slope management approaches should not be applied uniformly across the study area. Instead, mitigation measures should consider the specific soil characteristics developed from each geological formation (Duressa et al., 2024; Rahayu et al., 2023; Tavoularis, 2023), particularly in locations where high moisture content, elevated plasticity, and reduced shear strength may increase susceptibility to slope failure during periods of intense rainfall.

From a geological perspective, landslides in the study area are associated with soils developed from both the Kebobutak and Semilir Formations. The Kebobutak Formation, composed of pyroclastic breccia overlain by tuff and lapilli layers, tends to produce weathered materials that may develop relatively weak soil structures, particularly on steep slopes. Meanwhile, soils derived from the Semilir Formation are dominated by fine-grained pyroclastic deposits that tend to develop higher plasticity and greater water retention capacity. These characteristics can facilitate the buildup of pore water pressure during rainfall events, which in turn reduces effective stress and shear strength, increasing the likelihood of slope failure.

In contrast, soils derived from the Nglanggeran Formation generally exhibit coarser materials and slightly higher internal friction angles than soils developed on the Semilir Formation. These characteristics may provide relatively higher shear resistance under normal conditions. However, the steep geomorphological setting commonly associated with the Nglanggeran Formation may still contribute to slope instability, particularly where intense weathering and surface water infiltration occur. Therefore, despite showing relatively stronger soil mechanical properties, slopes developed on this formation cannot be considered entirely stable and still require proper slope management (Qi et al., 2025; Susanti et al., 2021; Yang et al., 2024).

From a mitigation perspective, slope management in these formations should prioritize strategies that reduce excessive water infiltration and maintain soil structural stability (Alam et al., 2024; Chen and Chui, 2025; Sharma, 2025). Measures such as improving surface drainage systems, maintaining vegetation cover, and regulating land use on steep slopes can help minimize landslide risk (Choi and Cheung, 2013; Hamza et al., 2025; Kamal et al., 2023; Murgia et al., 2024; Putra et al., 2025). In addition, the presence of relatively similar soil characteristics between landslide and non-landslide areas suggests that slopes currently classified as stable may still possess potential susceptibility to future landslides (Alcântara et al., 2025; Tu et al., 2025). Integrating geological information with soil physical and mechanical properties provides a more comprehensive understanding of the factors influencing slope instability in the Watugede Sub-Watershed. This approach allows landslide mitigation planning to consider not only external triggering factors but also the inherent characteristics of soil developed from different geological formations.

An important contribution of this study is the demonstration that geological formations influence landslide susceptibility indirectly by controlling soil physical and mechanical properties. The results indicate that differences in parent material and weathering characteristics generate contrasting soil behaviors, which subsequently affect shear resistance and slope stability. This finding highlights the importance of incorporating geological variability into landslide mitigation planning, particularly in tropical volcanic landscapes where lithological heterogeneity is often pronounced.

4. Conclusion

This study examined the influence of geological formations on soil physical and mechanical properties and their relationship to landslide occurrence in the Watugede Sub-Watershed, part of the Oyo River Basin in Gunungkidul Regency. The results indicate that soils developed from different volcanic formations exhibit distinct physical and mechanical characteristics that influence slope stability. Landslide locations are generally associated with soils that have higher moisture content, higher plasticity, and lower shear strength parameters compared to non-landslide areas. Among the studied formations, soils derived from the Semilir Formation tend to show greater susceptibility to slope instability due to their finer pyroclastic materials, higher water retention capacity, and relatively lower internal friction angles. At the same time, the Kebobutak Formation also demonstrates landslide occurrence associated with weathered pyroclastic breccia materials. Although soils derived from the Nglanggeran Formation tend to exhibit relatively stronger mechanical properties, steep geomorphological conditions may still contribute to potential slope instability. These findings highlight the importance of incorporating geological formation and soil physical and mechanical properties into landslide susceptibility assessment and slope management programs. Areas developed on the Semilir Formation should receive particular attention due to their relatively higher plasticity, greater water-retention capacity, and lower shear resistance, which increase vulnerability to slope failure during periods of intense rainfall. In contrast, mitigation efforts in the Kebobutak and Nglanggeran Formations should emphasize slope drainage improvement, vegetation management, and continuous monitoring of weathered slope materials, particularly on steep terrain. The results also provide useful information for spatial planning and land-use management by identifying geological formations that require more cautious development and infrastructure placement. However, this study was limited to several representative sampling locations, and further investigations involving broader spatial coverage and additional geotechnical parameters are recommended to improve understanding of landslide processes in volcanic terrains.

References

Adekiya, A.O., Ajayi, G.A., Adegbite, K.A., Imhanze, F.L., Ibaba, A.L. 2024. Mineralogical compositions of soils under three geological formations in some parts of Ogun state, Nigeria and their agricultural potentials. Scientific Reports 14(1), 6905. https://doi.org/10.1038/s41598-024-57397-0

Ahmad, A., Lopulisa, C., Baja, S., Imran, A.M. 2019. The correlation of soil liquid limit and plasticity index for predicting soil susceptibility: A case study on landslides area in South Sulawesi. IOP Conference Series: Earth and Environmental Science 235, 012007. https://doi.org/10.1088/1755-1315/235/1/012007

Ahmad, A., Solle, M.S., Lopulisa, C. 2020. Soil development from volcanic ash based on different pyroclastic composition. Journal of Tropical Soils 24(3), 135–140. https://doi.org/10.5400/jts.2019.v24i3.135-140

Alam, Md.J.B, Manzano, L.S., Debnath, R., Ahmed, A.A. 2024. Monitoring slope movement and soil hydrologic behavior using IoT and AI technologies: A systematic review. Hydrology 11(8), 111. https://doi.org/10.3390/hydrology11080111

Albarki, G.K., Sizilia, V.J., Kurniawan, S., Kusuma, Z., Utami, S.R. 2025. Temporarily degraded physical properties of pyroclastic materials from Mount Semeru: Can they be improved after reclamation with vegetation and indigenous microbes? Journal of Degraded and Mining Lands Management 12(5), 8865–8874. https://doi.org/10.15243/jdmlm.2025.125.8865

Alcántara-Ayala, I. 2025. Landslides in a changing world. Landslides 22(9), 2851–2865. https://doi.org/10.1007/s10346-024-02451-1

Alcântara, E., Baião, C.F., Guimarães, Y.C., Mantovani, J.R., Marengo, J.A. 2025. Machine learning reveals lithology and soil as critical parameters in landslide susceptibility for Petrópolis (Rio de Janeiro State, Brazil). Natural Hazards Research 5(3), 539–553. https://doi.org/10.1016/j.nhres.2025.01.008

Alghamdi, A.G., Majrashi, M.A., Ibrahim, H.M. 2023. Improving the physical properties and water retention of sandy soils by the synergistic utilization of natural clay deposits and wheat straw. Sustainability 16(1), 46. https://doi.org/10.3390/su16010046

Alnaimy, M., Elrys, A., Zelenakova, M., Pietrucha-Urbanik, K., Merwad, A.-R. 2023. The vital roles of parent material in driving soil substrates and heavy metals availability in arid alkaline regions: A case study from Egypt. Water 15(13), 2481. https://doi.org/10.3390/w15132481

Amalia, G., Minaka, U.S., Aprilianda, A. 2025. Karakteristik parameter kuat geser tanah pada lereng akibat perubahan kadar air tanah. Jurnal Teknik Sipil 21(1), 174–188. https://doi.org/10.28932/jts.v21i1.7509 (in Indonesian)

Amiri, A.A., Malidarreh, N.R., Kutanaei, S.S., Seyedkazemi, A., Davoudi-Ki, A. 2026. Enhancing the mechanical and shear behavior of clay soil using lime, Nano-MgO, and recycled PET fibers: experimental and UPV-based assessment. Scientific Reports 16(1), 7548. https://doi.org/10.1038/s41598-026-38956-z

Anda, M., Purwanto, S., Dariah, A., Watanabe, T., Dahlgren, R.A. 2023. A 200-year snapshot of soil development in pyroclastic deposits derived from the 1815 super explosive eruption of Mount Tambora in Indonesia. Geoderma 433, 116454. https://doi.org/10.1016/j.geoderma.2023.116454

Appukuttan, A., Deshpande, G., Jadhav, A., Reghunath, R. 2025. Geospatial modeling of landslide susceptibility in lateritic terrain: insights from machine learning techniques—random forest and DBSCAN. Discover Applied Sciences 7(10), 1224. https://doi.org/10.1007/s42452-025-07245-1

Arrisaldi, T., Wilopo, W., Fathani, T.F. 2021. Landslide susceptibility mapping and their rainfall thresholds model in Tinalah Watershed, Kulon Progo District, Yogyakarta Special Region, Indonesia. Journal of Applied Geology 6(2), 112-118. https://doi.org/10.22146/jag.59185

Asniar, N., Purwana, Y.M., Surjandari, N.S. 2019. Tuff as rock and soil: Review of the literature on tuff geotechnical, chemical and mineralogical properties around the world and in Indonesia. AIP Conf. Proc. 2114, 050022. https://doi.org/10.1063/1.5112466

Azarafza, M., Bonab, H.M., Derakhshani, R. 2022. A novel empirical classification method for weak rock slope stability analysis. Scientific Reports 12(1), 14744. https://doi.org/10.1038/s41598-022-19246-w

Baldermann, A., Dietzel, M., Reinprecht, V. 2021. Chemical weathering and progressing alteration as possible controlling factors for creeping landslides. Science of The Total Environment 778, 146300. https://doi.org/10.1016/j.scitotenv.2021.146300

Bilotta, E., Cascini, L., Foresta, V., Sorbinow, G. 2005. Geotechnical characterisation of pyroclastic soils involved in huge flowslides. Geotechnical and Geological Engineering 23(4), 365–402. https://doi.org/10.1007/s10706-004-1607-3

Budianta, W., Ohta, H., Takemura, J. 2022. The effect of clay-soil on landslide: Case study from Central Java, Indonesia. IOP Conference Series: Earth and Environmental Science 1091(1), 012012. https://doi.org/10.1088/1755-1315/1091/1/012012

Bunn, M., Leshchinsky, B., Olsen, M.J. 2020. Geologic trends in shear strength properties inferred through three-dimensional back analysis of landslide inventories. Journal of Geophysical Research: Earth Surface 125(9), e2019JF005461. https://doi.org/10.1029/2019JF005461

Cahyadhi, A., Putra, P., Nyoman, D., Triani, D., Putu, N., Surya, N., Tilija, D., Wirastuti, P.V., Widhaningtyas, T.U. 2025. Spatial multi-parameter analysis of landslide susceptibility with geological structure integration. Spatial Review for Sustainable Development 2(2), 129–145. https://doi.org/10.61511/srsd.v2i2.2025.2013

Chen, B., Chui, T.F.M. 2025. A review on implementing sustainable drainage systems in sloping environments: Understanding, approaches, and opportunities. Journal of Hydrology 661, 133577. https://doi.org/10.1016/j.jhydrol.2025.133577

Chen, J., Lei, X., Zhang, H., Lin, Z., Wang, H., Hu, W. 2021. Laboratory model test study of the hydrological effect on granite residual soil slopes considering different vegetation types. Scientific Reports 11(1), 14668. https://doi.org/10.1038/s41598-021-94276-4

Chen, Z., Zhao, M., Jiang, S., Tan, Q., Ma, Y., Li, Y., Yang, X. 2026. Mechanical properties of landslide slip zone soil considering over consolidation ratio and particle grading factors. Scientific Reports 16(1), 5769. https://doi.org/10.1038/s41598-026-36391-8

Cheng, J., Liu, Y., Xu, C., Xu, J., Sun, M. 2024. Study on the influence of pore water pressure on shear mechanical properties and fracture surface morphology of sandstone. Scientific Reports 14(1), 5761. https://doi.org/10.1038/s41598-024-55834-8

Chisambi, C.M., Shinjo, H. 2026. Influence of parent materials, landforms and climate on the soil properties distribution in northern and central Malawi. Geoderma Regional 44, e01047. https://doi.org/10.1016/j.geodrs.2025.e01047

Choi, K.Y., Cheung, R.W.M. 2013. Landslide disaster prevention and mitigation through works in Hong Kong. Journal of Rock Mechanics and Geotechnical Engineering 5(5), 354–365. https://doi.org/10.1016/j.jrmge.2013.07.007

Cordoba, J.P., Mergili, M., Aristizábal, E. 2020. Probabilistic landslide susceptibility analysis in tropical mountainous terrain using the physically based r.slope.stability model. Natural Hazards and Earth System Sciences 20, 815–829. https://doi.org/10.5194/nhess-20-815-2020

D'Addario, E., Giorgetti, G., Magrini, C., Disperati, L. 2023. Weathering effects on engineering geological properties of trachydacitic volcanic rocks from the Monte Amiata (Southern Tuscany, Italy). Geosciences 13(10), 299. https://doi.org/10.3390/geosciences13100299

Delorme, P., Voller, V., Paola, C., Devauchelle, O., Lajeunesse, É., Barrier, L., Métivier, F. 2017. Self-similar growth of a bimodal laboratory fan. Earth Surface Dynamics 5(2), 239–252. https://doi.org/10.5194/esurf-5-239-2017

Deng, A., Fang, Q., Geng, Q., Hong, H., Zhao, L., Liu, C., Cai, X., Wang, Y. 2025. Clay mineralogical and geochemical responses to weathering of intrusive vs. extrusive rocks under a subtropical climate. Applied Clay Science 264, 107644. https://doi.org/10.1016/j.clay.2024.107644

Di Maio, R., Salone, R., De Paola, C., Carbonari, R., Cusano, D., De Vita, P. 2024. Geotechnical and geophysical property models of soil-covered slopes prone to landsliding. The case study of the Ischia Island (Southern Italy). CATENA 247, 108509. https://doi.org/10.1016/j.catena.2024.108509

Duressa, A.A., Feyissa, T.A., Tukura, N.G., Gudeta, B.G., Gechelu, F.G., Bibi, T.S. 2024. Identification of soil erosion-prone areas for effective mitigation measures using a combined approach of morphometric analysis and geographical information system. Results in Engineering 21, 101712. https://doi.org/10.1016/j.rineng.2023.101712

Elankumaran, B., de Graaf, K.L., Orense, R.P. 2024. Understanding the geotechnical behaviour of pumiceous soil: A review. Geotechnics 4(4), 1189–1227. https://doi.org/10.3390/geotechnics4040061

Espinosa Fuentes, S.A., El Naggar, M.H. 2025. Uncertainty analysis and quantification of rainfall-induced slope instability in fine-grained clayey soils. Geotechnics 5(2), 31. https://doi.org/10.3390/geotechnics5020031

Hakim, D.L., Machalett, B., Adji, R., Satwhikawara, R., Alam, S. 2024. Soil morphological characteristics in the active volcanic toposequence zone at Tangkuban Parahu volcano, Indonesia. Jurnal Ilmiah Pertanian 21(2), 103–116. https://doi.org/10.31849/jip.v21i2.20956

Hamza, A., Talha, M., Shah, A., Khokhar, S.A., Khan, M.H., Khushnood, R.A., Ahmed, T. 2025. Advanced structural interventions for slope stabilization and disaster resilience. Discover Geoscience 3(1), 138. https://doi.org/10.1007/s44288-025-00199-2

Harabinova, S., Kotrasova, K., Panulinova, E. 2026. Comparison of limit equilibrium and finite element method for slope stability analysis. Buildings 16(3), 577. https://doi.org/10.3390/buildings16030577

Indratmoko, S., Koestoer, R.H. 2025. Landslide characteristics triggering evacuations: A comparative study of community responses and disaster management approaches. Calamity: A Journal of Disaster Technology and Engineering 2(2), 100-115. https://doi.org/10.61511/calamity.v2i2.2025.1437

Indrawan, I.G.B., Rahardjo, H., Leong, E.C. 2006. Effects of coarse-grained materials on properties of residual soil. Engineering Geology 82(3), 154–164. https://doi.org/10.1016/j.enggeo.2005.10.003

Indrawan, I.G.B., Tamado, D., Abrar, M., Warmada, I.W. 2024. Mineralogical and engineering properties of soils derived from in situ weathering of tuff in Central Java, Indonesia. Geosciences (Switzerland) 14(8), 213. https://doi.org/10.3390/geosciences14080213

Kamal, A.S.M.M., Hossain, F., Ahmed, B., Rahman, M.Z., Sammonds, P. 2023. Assessing the effectiveness of landslide slope stability by analysing structural mitigation measures and community risk perception. Natural Hazards 117(3), 2393–2418. https://doi.org/10.1007/s11069-023-05947-6

Kang, X., Wang, S., Wu, W., Xu, G., Zhao, J., Liu, F. 2022. Soil–water interaction affecting a deep-seated landslide: From field monitoring to experimental analysis. Bulletin of Engineering Geology and the Environment 81(2), 82. https://doi.org/10.1007/s10064-021-02556-0

Khadka, P., Kolawole, O. 2026. Insights into clay contributions to slope instability in coastal areas: Hydraulic and mechanical properties. Progress in Engineering Science 3(1), 100189. https://doi.org/10.1016/j.pes.2025.100189

Khan, M.I., Wang, S. 2021. Slope stability analysis to correlate shear strength with slope angle and shear stress by considering saturated and unsaturated seismic conditions. Applied Sciences 11(10), 4568. https://doi.org/10.3390/app11104568

Kinde, M., Getahun, E., Jothimani, M. 2024. Geotechnical and slope stability analysis in the landslide-prone area: A case study in Sawla – Laska road sector, Southern Ethiopia. Scientific African 23, e02071. https://doi.org/10.1016/j.sciaf.2024.e02071

Kumari, N., Mohan, C. 2021. Basics of clay minerals and their characteristic properties. In Clay and Clay Minerals. IntechOpen. https://doi.org/10.5772/intechopen.97672

Larimer, J.E., Yanites, B.J., Jung, S.J. 2022. A field study on the lithological influence on the interaction between weathering and abrasion processes in bedrock rivers. Journal of Geophysical Research: Earth Surface 127(4), e2021JF006418. https://doi.org/10.1029/2021JF006418

Li, C., Cai, Y. 2020. Effect of soil strength degradation on slope stability. International Journal of Design & Nature and Ecodynamics 15(4), 483–489. https://doi.org/10.18280/ijdne.150404

Liao, D., Deng, Y., Duan, X., Cai, C., Ding, S. 2022. Variations in weathering characteristics of soil profiles and response of the Atterberg limits in the granite hilly area of South China. CATENA 215, 106325. https://doi.org/10.1016/j.catena.2022.106325

Lima, A.P.B., Inda, A.V., Zinn, Y.L., da Silva, E.R., do Nascimento, P.C. 2022. Soil formation and properties along a sedimentary lithosequence in the ecotonal Cerrados of Mato Grosso, Brazil. CATENA 219, 106599. https://doi.org/10.1016/j.catena.2022.106599

Liu, H., Yu, H., Song, W., Li, T., Wu, J., Chen, H., Zhang, J., Xiao, Q. 2026. Chemical weathering intensity, element migration, and soil formation environment of the maoniushan granite-soil profile, Xichang, SW China. Minerals 16(3), 293. https://doi.org/10.3390/min16030293

Liu, X., Shao, S., Shao, S. (2024). Landslide susceptibility zonation using the analytical hierarchy process (AHP) in the Great Xi'an Region, China. Scientific Reports 14, 2941. https://doi.org/10.1038/s41598-024-53630-y

Liu, Y. 2025. Stability analysis of an expansive soil slope under heavy rainfall conditions with different anchor reinforcements. Scientific Reports 15(1), 819. https://doi.org/10.1038/s41598-024-84799-x

Luo, P., Ma, M. 2024. Failure mechanisms and protection measures for expansive soil slopes: A review. Sustainability 16(12), 5127. https://doi.org/10.3390/su16125127

Montanaro, C., Mortensen, A.K., Weisenberger, T.B., Dingwell, D.B., Scheu, B. 2021. Stratigraphic reconstruction of the Víti breccia at Krafla volcano (Iceland): insights into pre-eruptive conditions priming explosive eruptions in geothermal areas. Bulletin of Volcanology 83(11), 81. https://doi.org/10.1007/s00445-021-01502-y

Murgia, I., Vitali, A., Giadrossich, F., Tonelli, E., Baglioni, L., Cohen, D., Schwarz, M., Urbinati, C. 2024. Effects of land cover changes on shallow landslide susceptibility using SlideforMAP software (Mt. Nerone, Italy). Land 13(10), 1575. https://doi.org/10.3390/land13101575

Nofrizal, Fauzan, Hakam, A., Istijono, B., Setiawan, A., Aprisal. 2025. Laboratory study of geotechnical characteristics of soil in landslide-prone zone in Talamau District, West Pasaman Regency. Jurnal Penelitian Pendidikan IPA 11(8), 298–308. https://doi.org/10.29303/jppipa.v11i8.12046

Olivares, L., Picarelli, L. 2003. Shallow flowslides triggered by intense rainfalls on natural slopes covered by loose unsaturated pyroclastic soils. Géotechnique 53(2), 283–287. https://doi.org/10.1680/geot.53.2.283.37268

Prasetyaningtiyas, G.A., Priyono, K.D., Azhom, M.N., Anindyaputra, M.E. 2023. Pengaruh rembesan pada kuat geser tanah jenuh sebagian. Media Ilmiah Teknik Sipil 11(1), 40–47. https://doi.org/10.33084/mits.v11i1.4065 (in Indonesian)
Putra, M.S.G.P., Anggraini, N., Wahyuni, D. 2025. Landslide mitigation strategies in riverbank areas: A step-by-step guide to design retaining wall. Proceedings of the 8th FIRST 2024 International Conference on Global Innovations (FIRST-ESCSI 2024), pp. 134–142. https://doi.org/10.2991/978-94-6463-678-9_14
Qi, Z., Wang, Y., Li, T., Yan, X., Lan, Y., Zhang, X., Li, P., Lyu, L. 2025. Influence of post-fire root decay-induced soil macropores on slope stability: A new method for analyzing heterogeneous slope stability. International Soil and Water Conservation Research 13(3), 702–715. https://doi.org/10.1016/j.iswcr.2025.02.007
Rahayu, R., Supriyadi, S., Herdiansyah, G., Herawati, A., Erdaswin, F. 2023. The influence of geological formations on soil characteristics and quality in the southeast region of Pacitan Regency, Indonesia. Soil Science Annual 74(3), 1–13. https://doi.org/10.37501/soilsa/175383
Rodríguez, A.M., Román, A.Q. 2026. Integrating geomorphological and socio - spatial factors for landslide risk zonation in Atenas , Costa Rica. Discover Hazards 2, 8. https://doi.org/10.1007/s44475-026-00012-9
Santos, A.C.,da Silva, C.R., Neto, E.C.S., dos Anjos, L.H.C., Pereira, M.G. 2021. Weathering and pedogenesis of mafic rock in the Brazilian Atlantic Forest. Journal of South American Earth Sciences 111, 103452. https://doi.org/10.1016/j.jsames.2021.103452
Sarah, D., Zulfahmi, Z., Putra, M.H.Z., Madiutomo, N., Gunawan, G., Sumaryadi, S., Ahmid, D.A. 2024. Back analysis of rainfall-induced landslide in Cimanggung District of Sumedang Regency in West Java using deterministic and probabilistic analyses. Geosciences 14(12), 347. https://doi.org/10.3390/geosciences14120347
Sharma, D.R. 2025. Slope stability analysis in weak rock formations: Engineering implications and risk mitigation. International Journal of Geography, Geology and Environment 7(8), 35–45. https://doi.org/10.22271/27067483.2025.v7.i8a.392
Smith, E.J. 2026. Broad synthesis of factors and mechanisms contributing to time-dependent increase in axial capacity of driven, jacked, and vibrated piles. Geotechnical and Geological Engineering 44(1), 12. https://doi.org/10.1007/s10706-025-03432-4
Stock, F., Knipping, M., Pint, A., Ladstätter, S., Delile, H., Heiss, A.G., Laermanns, H., Mitchell, P.D., Ployer, R., Steskal, M., Thanheiser, U., Urz, R., Wennrich, V., Brückner, H. 2016. Human impact on Holocene sediment dynamics in the Eastern Mediterranean – the example of the Roman harbour of Ephesus. Earth Surface Processes and Landforms 41(7), 980–996. https://doi.org/10.1002/esp.3914
Susanti, P.D., Miardini, A., Harjadi, B. 2021. Disaster mitigation on lands affected by landslides in Banjarnegara Regency. IOP Conference Series: Earth and Environmental Science 916(1), 012026. https://doi.org/10.1088/1755-1315/916/1/012026
Swart, D., Dippenaar, M.A. 2025. Weathering profile of completely weathered rock from the Dullstroom Formation, South Africa. Bulletin of Engineering Geology and the Environment 84(5), 223. https://doi.org/10.1007/s10064-025-04224-z
Tavoularis, N. 2023. Soil erosion and landslide susceptibility mapping in Western Attica, Greece: A rock engineering system approach. Geosciences 13(11), 338. https://doi.org/10.3390/geosciences13110338
Tchuwa, I., Makande, M. 2025. Landslide susceptibility assessment using geotechnical characterization of collapsible and dispersive soils at Soche Hill, Blantyre, Malawi. Discover Geoscience 3(1), 133. https://doi.org/10.1007/s44288-025-00232-4
Tetteh, F.K., Abbey, S.J., Booth, C.A., Nukah, P.D. 2025. Current understanding and uncertainties associated with climate change and the impact on slope stability: A systematic literature review. Natural Hazards Research 5(3), 563–595. https://doi.org/10.1016/j.nhres.2025.01.011
Thounaojam, J.S., Ibotombi, S. 2024. Influence of clay on soil erodibility and landslides: Some examples from Manipur, Northeast India. Indian Geotechnical Journal 54(6), 2110–2125. https://doi.org/10.1007/s40098-023-00845-x
Troncone, A., Pugliese, L., Parise, A., Conte, E. 2023. Analysis of a landslide in sensitive clays using the material point method. Geotechnical Research 10(2), 67–77. https://doi.org/10.1680/jgere.22.00060
Tu, L., Chen, M., Leng, P., Liu, S., Liu, M., Luo, W., Mao, Y. 2025. Improving landslide susceptibility assessment through non-landslide sampling strategies. Land 14(10), 2059. https://doi.org/10.3390/land14102059
Ullah, R. 2021. Assessment of residual soil properties for slope stability analysis. International Journal of GEOMATE 21(86), 72-80. https://doi.org/10.21660/2021.86.j2282
Wang, F., Dai, Z., Takahashi, I., Tanida, Y. 2020. Soil moisture response to water infiltration in a 1-D slope soil column model. Engineering Geology 267, 105482. https://doi.org/10.1016/j.enggeo.2020.105482

Wang, H., Zou, J., Wang, X., Lv, P., Tan, Z., Cheng, L., Wei, Q., Qin, B., Guo, Z. 2024. Analysis of deformation mechanism of rainfall-induced landslide in the Three Gorges Reservoir Area: Piansongshu landslide. Scientific Reports 14(1), 10005. https://doi.org/10.1038/s41598-024-60590-w

Wilopo, W., Fathani, T. 2021. The mechanism of landslide-induced debris flow in geothermal area, Bukit Barisan mountains of Sumatra, Indonesia. Journal of Applied Engineering Science 19(3), 688–697. https://doi.org/10.5937/jaes0-29741

Wilson, M.J. 2019. The importance of parent material in soil classification: A review in a historical context. CATENA 182, 104131. https://doi.org/10.1016/j.catena.2019.104131

Yang, Z., Ding, X., Liu, X., Wahab, A., Ao, Z., Tian, Y., Bang, V.S., Long, Z., Li, G., Ma, P. 2024. Slope deformation mechanisms and stability assessment under varied conditions in an iron mine waste dump. Water 16(6), 846. https://doi.org/10.3390/w16060846

Yao, A.K., Tegan, E.S.N., Koffi, B.G., Kouamelan, A.N. 2025. Evidence of volcanic collapse and mass-wasting events in the Paleoproterozoic Toumodi Region (Côte d'Ivoire). Open Journal of Geology 15(10), 627–644. https://doi.org/10.4236/ojg.2025.1510031

Yulina, H., Arifin, M., Devnita, R., Djuwansah, M.R., Raidasari, F. 2025. The relationship between soil properties in pedogenesis dynamics: A study of pedons on slopes and basins. SAINS TANAH - Journal of Soil Science and Agroclimatology 22(2), 500. https://doi.org/10.20961/stjssa.v22i2.109149

Zaenurrohman, J.A., Zakaria, Z., Muljana, B., Sulaksana, N. 2025. The landslide problem in volcanic rocks of Java Island (Indonesia): A review from Integrating geotechnical engineering and geochemical perspectives. Engineering Geology and Hydrogeology 39(1), 111–126. https://doi.org/10.52321/igh.39.1.111

Zafra-Mejía, C.A., Hernández-Medina, D., Suárez, J., Naves, J., Anta, J. 2025. Understanding sediment wash-off in road drainage systems under intense rainfall and high sediment masses: Insights from a large-scale modeling facility. Science of The Total Environment 959, 178195. https://doi.org/10.1016/j.scitotenv.2024.178195

Zhang, M., Wang, W., Hao, Y., Liu, X., Zhang, R., Tian, Z., Huang, M., Zhang, J. 2025. Study on the formation mechanisms and stability of a gently inclined and shallow accumulative landslide. Scientific Reports 15(1), 15246. https://doi.org/10.1038/s41598-025-98031-x