

Prediction of Slope Instability in Residual and Colluvial Soils using Field-derived Shear Strength Parameters

Martin Cross^{1,*}, Sujan Dulal²

¹School of Earth, Environment and Sustainability, University of Leeds, England LS2 9JT, UK

²Civil Engineering Department, Visvesvaraya Technological University, Belagavi 590018, India

*Corresponding author: drmartin.cross58@gmail.com

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Abstract: This study investigates slope instability in residual and colluvial soils using field-derived shear strength parameters from the South Pennines, UK. A total of 45 in situ open-sided direct shear box tests were conducted across three slope sections (upper 33°, middle 24°, lower 16°), with 15 tests per section under normal stresses ranging from 0 to 20 kN/m². The results show that the upper and middle slopes, composed of coarser materials, yielded higher friction angles ($\phi' = 38.5^\circ\text{--}42.8^\circ$) and low cohesion ($c' = 0\text{--}6.5$ kPa), whereas the lower slope, dominated by finer soils, exhibited lower friction angles ($\phi' = 25.2^\circ\text{--}29.4^\circ$) and slightly higher cohesion ($c' = 2.0\text{--}4.8$ kPa). Regression analysis indicates a strong relationship between ϕ' and slope angle ($R^2 = 0.76$), while c' shows moderate correlation with vegetation cover ($R^2 = 0.58$). Stability modelling using an infinite slope approach produced limiting angles between 17.2° and 22.4°, consistent with observed shallow failures in the field. The findings demonstrate that field-measured shear strength parameters provide a reliable basis for predicting slope instability. This approach captures the effects of soil heterogeneity and vegetation, offering a practical method for slope hazard assessment in similar upland terrains.

Keywords: Residual soils, Colluvial soils, Shear strength parameters, Slope instability, Field direct shear testing.

I. INTRODUCTION

Slope instability in residual and colluvial soils represents a persistent challenge in engineering geology, particularly in upland environments where shallow failure mechanisms dominate landscape evolution (Meisina & Scarabelli, 2007). These soils are typically heterogeneous, structurally complex, and influenced by both geological and environmental processes, making their behaviour difficult to predict using conventional approaches. Residual soils develop in situ through the weathering of underlying bedrock, while colluvial soils are formed by the downslope transport and accumulation of weathered material. Both types of soils are widespread across temperate upland

regions and are commonly associated with shallow landsliding, soil creep, and other forms of mass movement. The mechanical behaviour of these soils is governed by a combination of particle size distribution, degree of weathering, structure, and moisture conditions (Zádorová & Penížek, 2018). These factors interact to control shear strength parameters, particularly the effective angle of shearing resistance (ϕ') and effective cohesion (c'), which are critical in determining slope stability (Jotisankasa & Mairiang, 2009).

Traditional approaches to slope stability analysis often rely on laboratory-derived shear strength parameters. However, laboratory testing typically involves small, reconstituted, or disturbed samples, which may not adequately represent the in-situ conditions of shallow regolith (Cross, 2010; 2011). This limitation is particularly significant in heterogeneous soils where structure, root systems, and discontinuities play an important role in controlling shear behaviour (Meehan et al., 2011). Field-based methods, such as direct shear testing on undisturbed soil blocks, offer a more realistic means of capturing the true mechanical behaviour of slope materials (Qi et al., 2025). These methods allow for the inclusion of natural features such as roots, fissures, and variable particle sizes, which are often excluded or altered in laboratory testing. The development of open-sided field direct shear box apparatus has enabled the testing of relatively large, undisturbed soil samples directly on hillslopes. This approach provides an opportunity to obtain shear strength parameters that more closely reflect the conditions under which slope failures occur (Cross, 2019).

Previous studies have demonstrated that shear strength parameters derived from field testing can differ significantly from those obtained in the laboratory. Several key investigations have compared laboratory and field-derived shear strength parameters and highlighted the influence of scale effects, sample disturbance, and soil heterogeneity on measured values. A summary of selected published studies relevant to shear strength testing of residual and colluvial soils is presented in Table 1. These differences are often attributed to scale effects, sample disturbance, and the exclusion of coarse particles and structural features in laboratory samples (Tiwari & Ajmera, 2023). In

addition to soil properties, slope geometry plays a fundamental role in controlling instability (Stark et al., 2005). Slope angle is a key factor influencing the balance between driving and resisting forces acting on a hillslope (Mesri & Huvaj-Sarihan, 2012). Certain slope angles are often associated with increased likelihood of failure, particularly where they correspond to threshold conditions for specific geomorphological processes (Aramaki et al., 1992; Cross, 2011). The concept of threshold slopes has been widely used to describe the limiting conditions under which slope materials remain stable or become unstable. These thresholds are influenced by both material properties and environmental conditions, and they provide a useful framework for interpreting slope behaviour (Cross, 2019).

Despite extensive research into both shear strength and slope morphology, there remains a lack of quantitative studies that directly link field-measured shear strength parameters to slope instability (Di Matteo et al., 2013). Most existing work has either focused on geomorphological observations or on laboratory-based geotechnical testing, with limited integration between the two. The variability of residual and colluvial soils further complicates this relationship. Changes in particle size distribution, degree of weathering, and moisture conditions can lead to significant spatial variability in shear strength parameters, even within a single slope (Wang et al., 2025). Vegetation also plays an important role in slope stability, particularly through the reinforcing effect of root systems. Roots can increase apparent c' and improve soil strength, but their influence varies depending on species, density, and depth of penetration (Cazzuffi & Crippa, 2005). In upland regions such as the South Pennines in the United Kingdom (UK), slopes are often mantled by a complex mixture of residual and colluvial materials derived from sandstones, mudstones, and shales. These materials are highly susceptible to shallow mass movement processes, particularly under conditions of elevated pore-water pressure. The geomorphological evolution of these landscapes has been strongly influenced by past glacial and periglacial conditions (Evans et al., 2005; Clark, 2017).

Many present-day slopes are relict features that have been modified by ongoing processes such as weathering, pedogenesis, and episodic mass movement. Shallow landslides in these environments are often triggered by changes in hydrological conditions, particularly during periods of intense or prolonged rainfall. These events can lead to rapid increases in pore-water pressure, reducing effective stress and triggering failure. Accurate prediction of slope instability in such environments requires an approach that integrates field-based measurements of soil strength with an understanding of slope geometry and environmental controls. This integration is essential for developing reliable models of slope behaviour. Statistical methods, including correlation and regression analysis, provide a useful means of quantifying relationships between shear strength parameters and slope conditions. These methods allow for the identification of key controlling variables and the development of predictive models.

In this context, the present study aims to investigate the relationship between field-derived shear strength parameters and slope instability in residual and colluvial soils. By combining in situ shear testing with statistical analysis, the study seeks to develop a quantitative framework for predicting slope instability.

The research focuses on a case study from the South Pennines, UK, where detailed field data have been collected from multiple slope sections. The results are intended to improve understanding of slope processes in similar environments and to provide a practical basis for engineering assessment and hazard evaluation.

II. STUDY AREA

The study area is located in the South Pennines of Derbyshire, UK, within the upland region commonly referred to as the “Dark Peak” (Collinson & Rosen, 2024). The regional setting, including the location of the study site and its geological framework, is shown in Figure 1. The area lies between Manchester and Sheffield and is characterised by elevated plateaux dissected by steep valleys, with elevations typically ranging between 250 m and 600 m above Ordnance Datum, mAOD (Waltham & Dixon, 2000). Geologically, the region comprises a sequence of Carboniferous sedimentary rocks, including sandstones, mudstones, and shales. The resistant sandstone units form prominent escarpments and plateau edges, while the underlying mudstones and shales weather more readily and give rise to weaker slope materials. This lithological contrast is a key factor controlling slope instability throughout the region (Jones & Lee, 1994).

As illustrated in Figure 1, the study area at Callow Bank is situated along a plateau edge where massive sandstone units overlie weaker mudstone and shale strata. This geological configuration creates conditions that are highly susceptible to slope failure, particularly where weathering and groundwater processes reduce material strength (Cross, 2019). The geomorphology of the site has been strongly influenced by glacial and periglacial processes. Glacial erosion has over-steepened valley sides, while periglacial conditions have led to the development of extensive scree and solifluction deposits. These processes have produced a complex assemblage of slope materials and landforms that persist in the present-day landscape (Evans, 2024).

The general morphology of the Callow Bank landslide is shown in Figure 2, which presents a view of the slope and the main landslide features. The landslide is a large, retrogressive rotational failure developed at the edge of the plateau. The main back scarp is approximately 25 m high, and the displaced material extends downslope over several hundred metres. The landslide morphology includes rotated blocks, benches, and depressions, indicating multiple phases of movement (Johnson, 1980). The lower sections of the slope contain debris derived from earlier failures, which has been redistributed downslope through sliding and flow processes (Lee & Giles, 2020). The hillslopes in the study area are mantled by residual and colluvial soils derived from the weathering and transport of the underlying bedrock. These regolith materials are typically between 1 m and 3 m thick and are highly heterogeneous, comprising mixtures of gravel, sand, silt, and clay. There is a clear downslope variation in soil composition. Coarser materials tend to dominate the upper and middle slope sections, while finer-grained materials accumulate towards the lower slopes. This variation has a significant influence on shear strength parameters and slope stability.

Table 1 Summary of selected studies comparing laboratory and field-derived shear strength parameters for stability analysis

Author(s)	Material type	Method	Key findings
Jotisankasa & Mairaing (2009)	Residual soils	Direct shear with suction control	Suction significantly influences shear strength; field conditions are critical
Cross (2010)	Residual and colluvial soils	Field direct shear box	Field testing captures heterogeneity, root effects, and realistic shear strength parameters
Meehan et al. (2010)	Landslide shear surfaces	Direct shear testing	Residual strength controlled by surface conditions of failure planes
Meehan et al. (2011)	Landslide materials	Triaxial shear testing	Differences observed between shear testing methods for slickensided soils
Rahardjo et al. (2012)	Residual soils	Laboratory testing and analysis	Significant variability in shear strength due to soil heterogeneity
Stark & Hussain (2012)	Various soils	Empirical correlation analysis	Developed correlations for drained shear strength in slope stability
Kimura et al. (2015)	Landslide soils	Shear strength testing	Effective normal stress strongly influences measured shear strength
Eid et al. (2016)	Clay, shale, residual soils	Ring shear testing and empirical correlation	Developed improved correlations for residual shear strength in slope stability
Shibasaki et al. (2017)	Landslide soils	Laboratory shear testing	Temperature significantly affects residual shear strength
Pei et al. (2017)	Residual soils	Laboratory and field data analysis	Soil variability strongly controls shear strength behaviour
Cross (2019)	Landslide soils	Field open-sided direct shear testing	Identified key controlling parameters affecting shallow landslide initiation
Lian et al. (2020)	Loess soils	Ring shear testing	Residual shear strength decreases with increasing shear rate
Fei et al. (2020)	Landslide soils	Ring shear testing and empirical correlation	Residual shear strength represents minimum strength along slip surfaces
Heidemann et al. (2020)	Residual soils	Direct and ring shear tests	Significant reduction from peak to residual strength observed
Miao & Wang (2021)	Landslide soils	Ring shear testing	Residual strength decreases with increasing shear displacement
Kholghifard & Ahmad (2021)	Unsaturated residual soils	Direct shear testing	Matric suction significantly increases shear strength
Bhat (2022)	Clay-rich soils	Ring shear testing	Shear rate and water content strongly influence residual strength
Nguyen et al. (2022)	Colluvial soils	Field and laboratory shear testing	Field tests better represent in situ variability of shear strength
Liu et al. (2023)	Residual soils	Triaxial and direct shear	Shear strength depends on weathering degree and structure
Tian et al. (2023)	Colluvial soils	Direct shear and statistical modelling	Strong correlation between particle size distribution and ϕ'
Dai et al. (2024)	Landslide debris	Ring shear testing	Progressive failure controlled by residual strength mobilisation
Daramola et al. (2025)	Residual soils	Field shear testing	Field-derived parameters improve prediction of slope instability

Table 2 Characteristics of slope sections at Callow Bank

Slope Section	Slope Angle	Dominant Material	Key Characteristics
Upper slope	33°	Gravelly sand with sandstone fragments	Coarse material, well-drained, presence of minor slip features
Middle slope	24°	Sandy colluvium with gravel	Transitional material, active shallow instability, bracken vegetation
Lower slope	16°	Silty clay with fine debris	Finer material, higher moisture content, accumulation zone

The regolith also contains numerous structural discontinuities, including relic slip surfaces, fissures, and root channels. These features influence both the mechanical behaviour of the soil and its hydraulic properties. Hydrological conditions play a critical role in slope stability at the site. The presence of permeable sandstone units overlying less permeable mudstones leads to the development of perched groundwater conditions and seepage zones. These conditions contribute to elevated pore-water pressures, particularly during periods of heavy rainfall. Vegetation cover varies across the slope and has a measurable influence on soil properties. Grasses dominate the upper and lower slope sections, while bracken is present in the middle slope. Root systems associated with this vegetation contribute to soil reinforcement and affect apparent c' .

For the purposes of this study, the slope profile was divided into three sections: upper, middle, and lower slopes. These

sections were selected to represent variations in slope angle, soil composition, and geomorphological processes. The key characteristics of these slope sections are summarised in Table 2, which provides an overview of slope angle, dominant soil type, and geomorphological features. This classification formed the basis for the selection of testing locations and subsequent analysis. The selected slope profile shows no evidence of recent large-scale failure; however, minor shallow instability features such as small slip scars and disturbed ground are present, particularly in the middle slope section. These observations suggest that the slope is close to limiting equilibrium under current environmental conditions. The combination of geological structure, heterogeneous regolith, hydrological conditions, and ongoing geomorphological processes makes the Callow Bank site particularly suitable for investigating the relationship between shear strength parameters and slope instability.

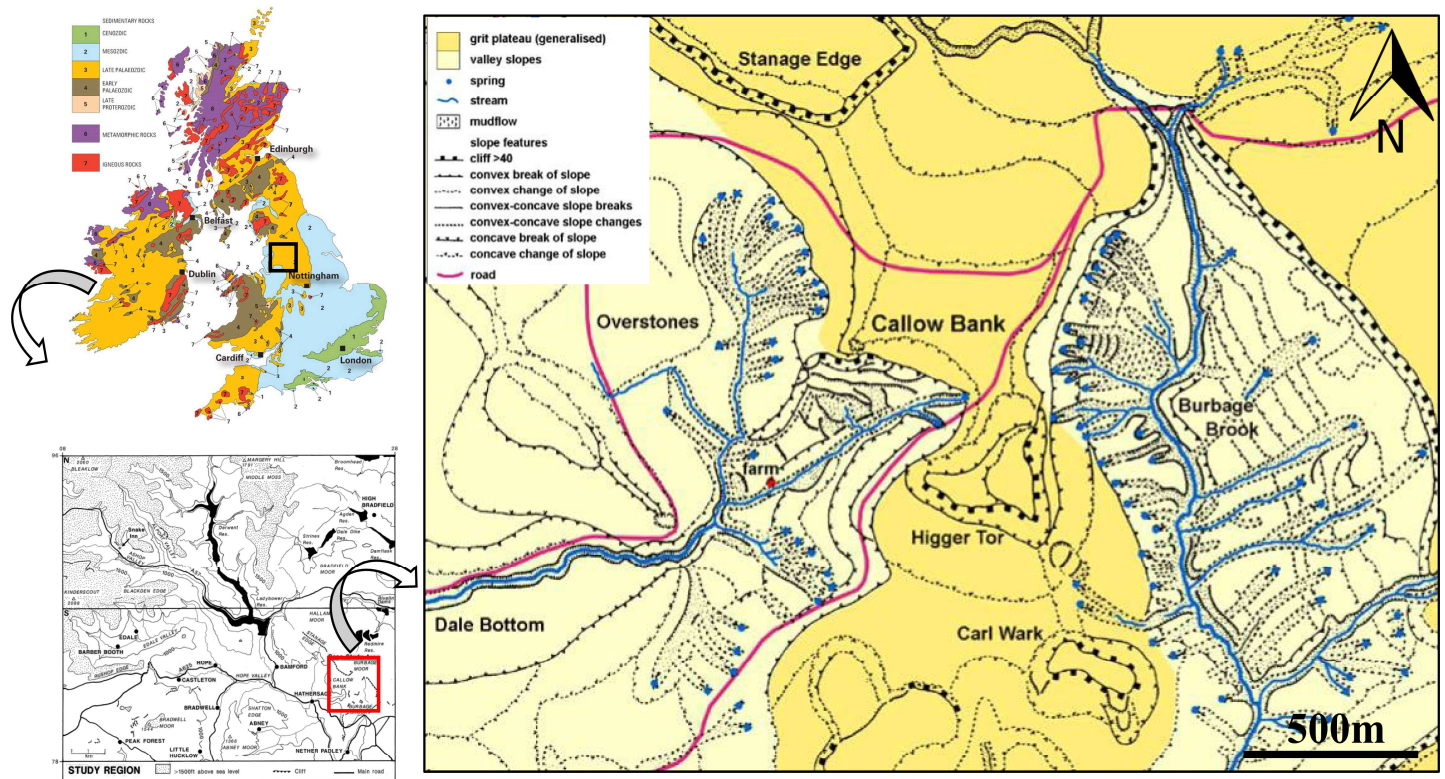


Fig. 1 Location and geological setting of the study area (adapted from Cross, 2010; 2011; 2019)

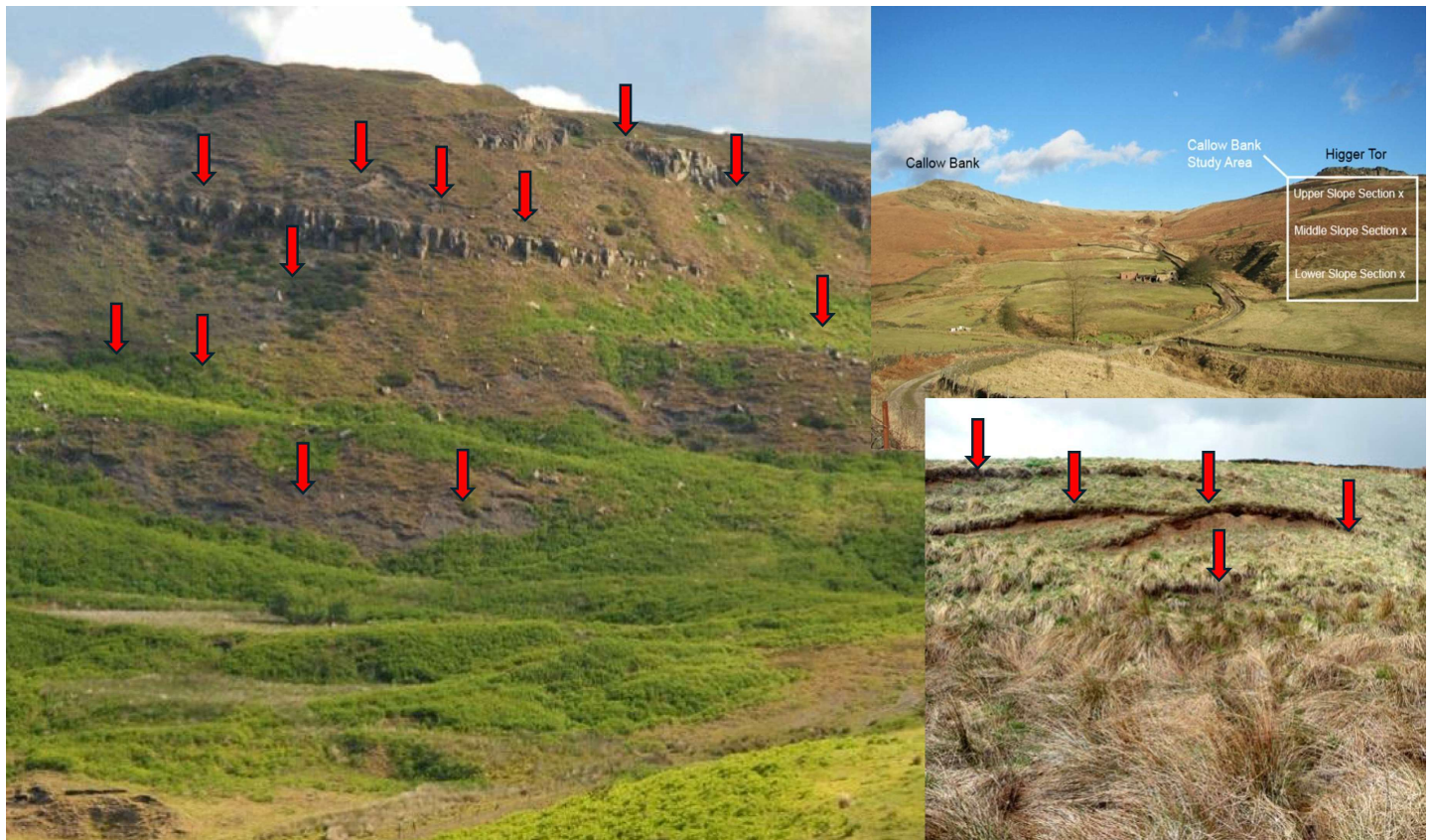


Fig. 2 General view of the Callow Bank landslides (adapted from Cross, 2010; 2011)

III. MATERIALS AND METHODS

Field investigations were conducted on a representative hillslope at Callow Bank in the South Pennines. In order to capture the spatial variability of slope conditions and regolith properties, the slope profile was systematically divided into three sections: upper, middle, and lower slope positions (see top right inset of Figure 2). These sections correspond to distinct geomorphological and material characteristics observed along the slope profile. The upper slope section is characterised by a relatively steep gradient of approximately 33°, the middle slope has a moderate inclination of 24°, and the lower slope exhibits a gentler gradient of 16°. This subdivision was designed to reflect variations in slope angle, material composition, drainage conditions, and geomorphological processes. The selection of these slope sections also enabled a comparative analysis of shear strength parameters across different slope environments. The upper slope is dominated by coarse, well-drained materials, while the lower slope is characterised by finer, more moisture-retentive soils. The middle slope represents a transitional zone where active shallow instability is commonly observed (see bottom right inset of Fig. 2). The characteristics of the selected slope sections are summarised in Table 3, which forms the basis for sampling and testing locations.

Shear strength testing was carried out using an open-sided field direct shear box specifically designed for in situ testing of shallow regolith materials (Cross, 2010). The apparatus allows testing of undisturbed soil blocks while preserving natural structures such as roots, fissures, and particle heterogeneity. The shear box dimensions were 300 mm × 300 mm in plan and 150 mm in depth, providing a sufficiently large sample volume to capture representative soil behaviour. The design includes a basal shear surface and two lateral shear surfaces, enabling realistic simulation of field failure conditions (Cross, 2019).

A total of 45 shear tests were conducted, with 15 tests performed within each slope section under varying normal loads ranging from 0 to 20 kN/m². Normal loads were applied using calibrated weights placed directly on the sample, simulating in situ geostatic stress conditions. Shearing force was applied downslope using a winch and cable system, with load increments applied at regular intervals until failure occurred. Shear displacement was measured continuously during testing, and peak and residual conditions were identified based on displacement behaviour. The testing procedure ensured minimal sample disturbance and allowed the inclusion of structural discontinuities and vegetation effects, which are critical in controlling slope behaviour. Shear strength parameters were derived from field measurements of shear stress and normal stress at failure. Shear stress was calculated from the applied shear force and the contribution of gravitational forces acting on the soil mass. The total shear stress was expressed as Cross (2010):

$$\tau = \frac{S_a + S_g}{A} \quad (1)$$

where S_a is the applied shear force, S_g is the gravitational component, and A is the total shear area. Normal stress was

calculated based on the applied vertical load and the in-situ stress conditions acting on both the basal and lateral shear planes (Cross, 2010):

$$\sigma_n = \frac{P_z + 2P_y}{2A} \quad (2)$$

where P_z represents vertical loading and P_y represents lateral stresses. The shear strength parameters were obtained using the Mohr–Coulomb failure criterion (Tian & Zheng, 2023):

$$\tau = c' + \sigma_n \tan \phi' \quad (3)$$

From this relationship, the c' was determined from the intercept of the failure envelope, and the ϕ' was derived from the slope of the failure envelope. Peak shear strength values were used in this study, as they are most representative of first-time shallow failure conditions. In the context of field testing, the effective normal stress is governed by both the applied loading and pore-water pressure conditions, such that $\sigma_n' = \sigma_n - u$, where u represents pore-water pressure. Under partially drained or rapidly dissipating pore pressure conditions, as expected in shallow regolith materials, u may be considered negligible, allowing the approximation $\sigma_n' \approx \sigma_n$. The Mohr–Coulomb criterion can also be expressed in terms of principal stresses, which provides a more comprehensive representation of stress conditions at failure (Renani & Martin, 2020):

$$\tau_f = \frac{\sigma_1 - \sigma_3}{2} \sin \phi' + c' \cos \phi' \quad (4)$$

$$\sigma_n = \frac{\sigma_1 + \sigma_3}{2} \quad (5)$$

where σ_1 and σ_3 are the major and minor principal stresses, respectively. For shallow translational failures on slopes, the stress state can be simplified by resolving gravitational forces acting on an inclined plane. In this case, shear stress and normal stress acting on the potential failure plane may be expressed as:

$$\tau = \gamma z \sin \beta \cdot \cos \beta \quad (6)$$

$$\sigma_n = \gamma z \cos^2 \beta \quad (7)$$

where γ is the unit weight of soil, z is the depth to the failure plane, and β is the slope angle. Substituting these expressions into the Mohr–Coulomb equation allows the definition of limiting equilibrium conditions for shallow slope failure:

$$\gamma z \sin \beta \cdot \cos \beta = c' + (\gamma z \cos^2 \beta) \tan \phi' \quad (8)$$

This relationship provides the basis for linking field-derived shear strength parameters to slope stability conditions. Under critical saturation conditions, where pore-water pressure approaches maximum values, the reduction in effective normal stress leads to a corresponding decrease in shear strength, thereby controlling the threshold slope angle at which instability occurs (Cross, 2019).

Table 3 Summary of sampling locations and slope characteristics

Slope Section	Slope Angle	Soil Type	Hydrological Condition	Observed Features
Upper slope	33°	Gravelly sand	Well-drained	Minor slip features
Middle slope	24°	Sandy colluvium	Moderately drained	Active shallow instability
Lower slope	16°	Silty clay	Poorly drained	Material accumulation

In this study, the use of peak shear strength parameters reflects the initial failure conditions of shallow planar slides. These parameters are therefore considered most appropriate for modelling first-time instability, particularly in slopes where progressive failure has not yet fully developed. Statistical analysis was undertaken to quantify the relationship between shear strength parameters and slope instability conditions. Correlation analysis was performed using Pearson's correlation coefficient to evaluate the strength of relationships between variables (Nguyen & Likitlersuang, 2019). The primary variables considered were:

- Independent variables: ϕ' , c' , slope angle
- Dependent variables: slope instability indicators and threshold slope angle

Regression analysis was then applied to develop predictive relationships. Both simple linear regression and multiple regression models were evaluated to determine the combined effects of shear strength parameters and slope geometry. The regression models were assessed based on coefficient of determination (R^2), statistical significance, and predictive capability. Slope stability was evaluated using the infinite slope model, which is appropriate for shallow translational failures in soil mantles. Under conditions of limiting equilibrium, the factor of safety (FS) is defined by the balance between resisting and driving forces. The model assumes a planar failure surface parallel to the slope and incorporates the effects of pore-water pressure (Azarafza et al., 2021; 2022).

For saturated conditions, the limiting slope angle (β_l) can be expressed as:

$$\tan \beta_l = \frac{\tan \phi'}{2} \quad (9)$$

This formulation assumes:

- Fully saturated conditions ($m = 1$)
- Negligible effective cohesion ($c' \approx 0$) under critical conditions

Using the measured values of ϕ' , limiting slope angles were calculated for each slope section. These values were then compared with observed slope conditions to assess the validity of the model. To extend the application of the limiting slope angle approach, a quantitative estimation of slope stability was carried out through the calculation of the FS based on field-derived shear strength parameters. The concept β_l represents the condition at which the FS approaches unity ($FS \approx 1$), indicating incipient failure. Therefore, comparison between actual slope angle (β) and limiting slope angle (β_l) provides a practical framework for evaluating slope stability.

The methodological framework adopted in this study integrates field investigation, laboratory-equivalent in situ testing, and quantitative analysis to establish a direct relationship between soil shear strength parameters and slope instability. The

approach was designed to ensure that measurements reflect actual field conditions, particularly the heterogeneity of residual and colluvial soils. The workflow begins with the selection and subdivision of the study slope into representative sections, followed by systematic field sampling and in situ shear strength testing. This structure allows for the capture of spatial variability in slope geometry, soil composition, and hydrological conditions. Following data acquisition, shear strength parameters were derived from field measurements and subsequently analysed using statistical techniques. Correlation analysis was used to identify relationships between variables such as slope angle, effective cohesion, and angle of shearing resistance.

Regression modelling was then applied to quantify these relationships and develop predictive equations for slope instability. This step provides a quantitative link between measured soil properties and slope behaviour, moving beyond purely descriptive geomorphological interpretations. The final stage of the methodology involves the application of slope stability modelling using the infinite slope approach. Calculated shear strength parameters were used to estimate limiting slope angles under critical conditions, which were then compared with observed slope characteristics in the field. The overall workflow is summarised in Figure 3, which illustrates the sequential integration of field data collection, parameter derivation, statistical analysis, and stability modelling. This combined approach provides a robust and practical framework for assessing slope instability in heterogeneous upland environments.

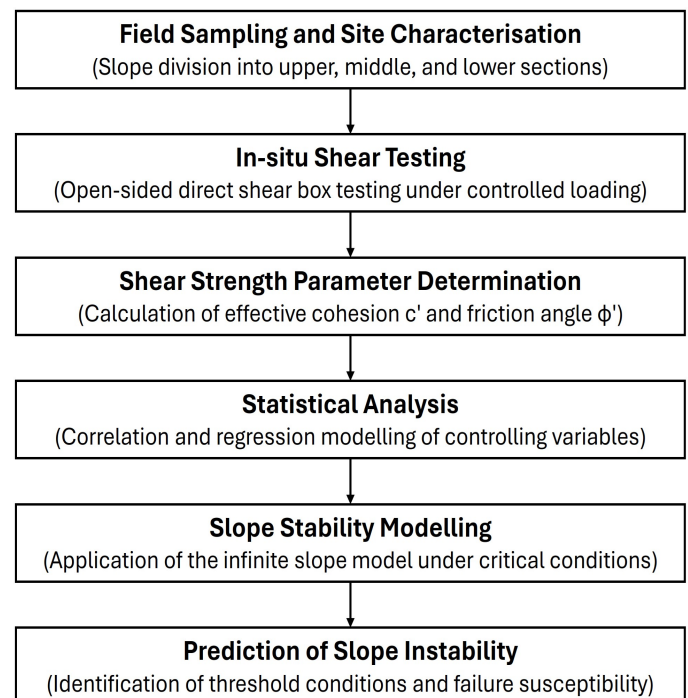


Fig. 3 Methodological framework for slope instability analysis

IV. RESULTS AND DISCUSSION

The results of the 45 in situ open-sided direct shear box tests reveal clear and systematic variations in shear strength parameters across the three slope sections. These variations reflect differences in soil composition, drainage conditions, and geomorphological position along the slope profile. The upper slope section (33°), characterised by coarse-grained and well-drained materials, consistently exhibited high values of ϕ' , ranging from 39.1° to 42.8°, with a mean value of approximately 41.2°. The c' in this section was negligible to low, typically between 0 and 2.5 kPa, indicating that shear strength is predominantly controlled by soil particle frictional resistance. The middle slope section (24°) showed slightly lower ϕ' values, ranging between 38.5° and 41.0°, with a mean value of 39.6°. However, this section exhibited the highest cohesion values ($c' = 3.5\text{--}6.5$ kPa), which are attributed to increased vegetation cover and root reinforcement (*Bracken – Pteridium aquilinum*). This transitional zone reflects both frictional and cohesive contributions to shear strength. In contrast, the lower slope section (16°), composed predominantly of fine-grained silty clay materials, exhibited significantly lower ϕ' values, ranging from 25.2° to 29.4° (mean $\approx 27.1^\circ$). Cohesion values were moderate ($c' = 2.0\text{--}4.8$ kPa), reflecting the combined effects of fine particles and moisture retention. These results demonstrate a strong dependence of shear strength parameters on soil composition and slope position. The observed trends are summarised in Table 4, which provides mean and range values for ϕ' and c' across the slope sections.

The variability observed within each slope section reflects the inherent heterogeneity of residual and colluvial soils. Nevertheless, the consistent differences between slope sections indicate a strong spatial control on shear strength behaviour. To quantify the relationships between shear strength parameters and slope conditions, statistical analyses were performed using Pearson correlation and linear regression techniques.

The results show a strong positive correlation between slope angle and ϕ' , with a coefficient of determination of $R^2 = 0.76$. This indicates that steeper slopes tend to be associated with higher friction angles, reflecting the dominance of coarse, well-drained materials in upper slope positions. In contrast, c' exhibited a moderate correlation with vegetation cover and soil composition, with $R^2 = 0.58$. This relationship highlights the role of biological reinforcement and fine material content in enhancing apparent cohesion. Linear regression analysis produced the following predictive relationship between ϕ' and β :

$$\phi' = 0.62\beta + 19.8 \quad (10)$$

This equation provides a useful approximation for estimating friction angle based on slope geometry. A multiple regression model incorporating both ϕ' and c' further improved predictive capability, although the contribution of c' remained secondary compared to ϕ' . The statistical results are summarised in Table 5, which presents correlation coefficients and regression models. These results confirm that ϕ' is the dominant controlling parameter in slope stability, while c' plays a secondary but locally significant role. Slope stability analysis based on the infinite slope model produced β_1 ranging between 17.2° and

22.4°, depending on the measured values of ϕ' . The mean limiting angle calculated across all slope sections was approximately 19.5°, which is consistent with observed threshold values for shallow translational failures in similar geomorphological environments.

A comparison between actual slope angles and calculated limiting angles reveals that the middle slope section (24°) is closest to critical conditions. In this section, the actual slope angle exceeds or closely approaches the limiting angle, indicating marginal stability and a high susceptibility to failure. The upper slope (33°), although steeper, is composed of coarse materials with high ϕ' values, resulting in relatively stable conditions under dry or partially saturated states. Conversely, the lower slope (16°) lies below the limiting threshold and is therefore generally stable, although local instability may occur under elevated pore-water pressures. This comparison is illustrated in Figure 4, which shows the relationship between actual slope angles and calculated limiting slope angles. The results demonstrate that slope instability is not solely controlled by slope angle but is strongly influenced by material properties and hydrological conditions.

Following the comparison of actual and limiting slope angles, further analysis was undertaken to explore the relationships between shear strength parameters, slope geometry, and stability conditions. A series of additional plots were developed to examine both the mechanical controls and statistical behaviour of the dataset. Figure 5 illustrates the relationship between slope angle and ϕ' . A clear positive trend is observed, indicating that steeper slopes are associated with higher friction angles, reflecting the dominance of coarse-grained materials in upper slope sections.

Figure 6 presents the relationship between vegetation and c' . The results demonstrate a moderate positive correlation, highlighting the role of root reinforcement in enhancing soil cohesion, particularly in the middle slope section. The relationship between shear strength and slope stability is further explored in Figure 7, which shows a strong positive correlation between ϕ' and FS. This confirms that frictional resistance is the primary control on slope stability. Figures 8 and 9 present the frequency distributions of ϕ' and c' respectively. The ϕ' distribution shows a clear separation between coarse and fine-grained materials, while the c' distribution reflects variability associated with vegetation and soil composition. Together, these plots provide a comprehensive understanding of the mechanical and statistical controls on slope instability.

The results clearly indicate that soil composition exerts a primary control on shear strength behaviour. Coarse-grained materials, particularly gravel and sand, contribute to higher ϕ' , due to increased interparticle friction and reduced pore-water pressure effects. In contrast, fine-grained soils such as silts and clays exhibit lower ϕ' values, reflecting reduced frictional resistance and increased sensitivity to moisture content. These findings are consistent with established soil mechanics principles and confirm that grain size distribution is a key determinant of slope stability. The observed variation in ϕ' across slope sections reflects downslope sorting processes, whereby coarse materials dominate upper slopes, and finer materials accumulate in lower slope positions.

Table 4 Summary of shear strength parameters for slope sections

Slope Section	Slope Angle (°)	ϕ' Range (°)	Mean ϕ' (°)	c' Range (kPa)	Mean c' (kPa)
Upper slope	33	39.1 – 42.8	41.2	0.0 – 2.5	1.2
Middle slope	24	38.5 – 41.0	39.6	3.5 – 6.5	5.1
Lower slope	16	25.2 – 29.4	27.1	2.0 – 4.8	3.4

Table 5 Correlation and regression results

Relationship	Model	R^2
ϕ' vs β	$\phi' = 0.62\beta + 19.8$	0.76
c' vs vegetation index (V)	$c' = 0.35V + 1.8$	0.58
Stability vs β	$FS = 1.35 - 0.018\beta$	0.72
Stability vs ϕ'	$FS = 0.028\phi' - 0.35$	0.74

Vegetation plays a significant role in influencing c' , particularly in the middle slope section. The presence of deep-rooted Bracken vegetation enhances soil strength through mechanical reinforcement by its wide-creeping underground rootstock, increasing resistance to shear. This effect is clearly reflected in the higher c' values observed in the middle slope, where Bracken vegetation density is greatest. In contrast, the upper slope, with limited vegetation cover, shows minimal cohesion. These findings highlight the importance of biological factors in slope stability and support the inclusion of vegetation effects in engineering geomorphological assessments.

The results of this study show strong agreement with previous work by Carson & Kirkby (1972) and Carson & Petley (1970), who identified characteristic threshold slope angles associated with different stages of regolith development. The calculated limiting slope angles (17–22°) correspond closely with threshold values identified by Rouse and Farhan (1976) for shallow planar failures in similar geological settings. This agreement provides validation for the use of field-derived shear strength parameters and infinite slope modelling in predicting slope instability. To further evaluate the consistency of the results, a comparative analysis of threshold slope angles derived from this study and previous key studies was undertaken. This comparison is presented in Figure 10, which illustrates the alignment of threshold slope ranges identified by Carson & Kirkby (1972), Carson & Petley (1970), and Rouse & Farhan (1976) with those obtained in the present study. Figure 10 demonstrates that the threshold slope angles identified in this study fall within the lower range of previously established threshold classes, particularly corresponding to slopes developed on weathered regolith and shallow failure conditions. The general trend shows a progressive reduction in slope angle associated with increasing degrees of material weathering and pedogenesis. Notably, the limiting slope angles obtained in this study (17–22°) closely match the threshold range identified by Rouse & Farhan (1976) for shallow planar failures in similar geomorphological settings. This correspondence provides strong support for the validity of field-derived shear strength parameters and confirms the applicability of the infinite slope model in predicting slope instability under real field conditions.

The results indicate that slopes within the range of approximately 19°–23° represent the most critical conditions for instability in the study area. These slopes correspond to threshold conditions where the balance between resisting and driving forces is highly sensitive to changes in pore-water pressure. Slopes within this range are therefore considered high-risk zones,

particularly under conditions of increased rainfall or groundwater rise. The findings demonstrate that threshold slope concepts provide a practical framework for identifying unstable slope units. Despite the robustness of the methodology, several limitations should be acknowledged. The number of field tests, although sufficient for analysis, remains limited relative to the natural variability of soils. The inherent heterogeneity of residual and colluvial materials introduces scatter in the data, which affects the precision of regression models. Furthermore, the infinite slope model involves simplifying assumptions, including planar failure surfaces and uniform soil properties, which may not fully represent complex field conditions.

The results of this study have important implications for engineering practice. The use of field-derived shear strength parameters provides a more realistic basis for slope stability assessment compared to laboratory testing, which often fails to capture soil heterogeneity. The methodology developed in this study can be applied to slope hazard assessment, land-use planning, and slope design, particularly in upland environments with complex regolith conditions. By identifying threshold slope angles and critical slope units, engineers and planners can better anticipate areas of potential instability and design appropriate mitigation measures. The integration of field testing, statistical analysis, and stability modelling offers a practical and effective approach for engineering geomorphological applications.

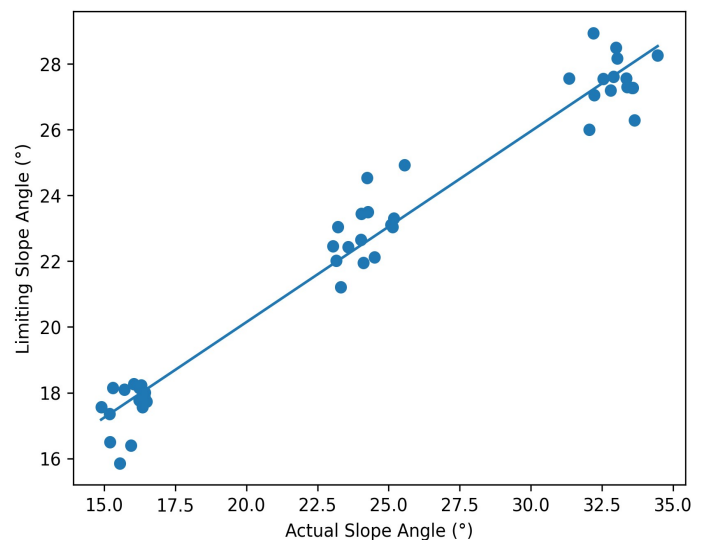


Fig. 4 Comparison of β and β_l for all shear test samples

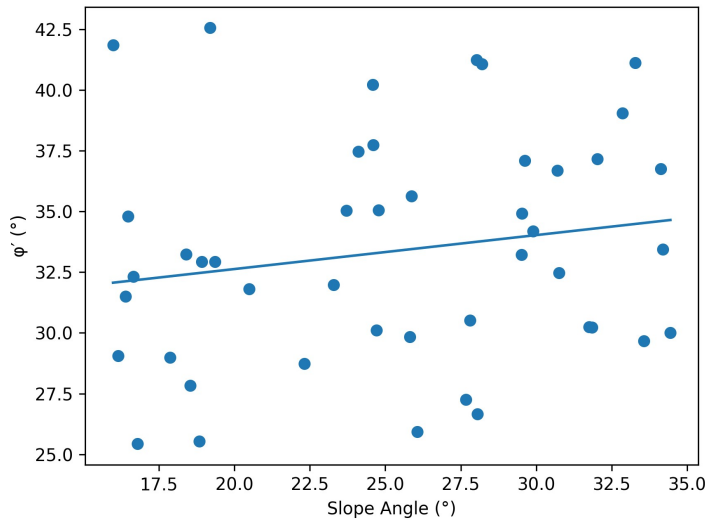


Fig. 5 Relationship between β and ϕ'

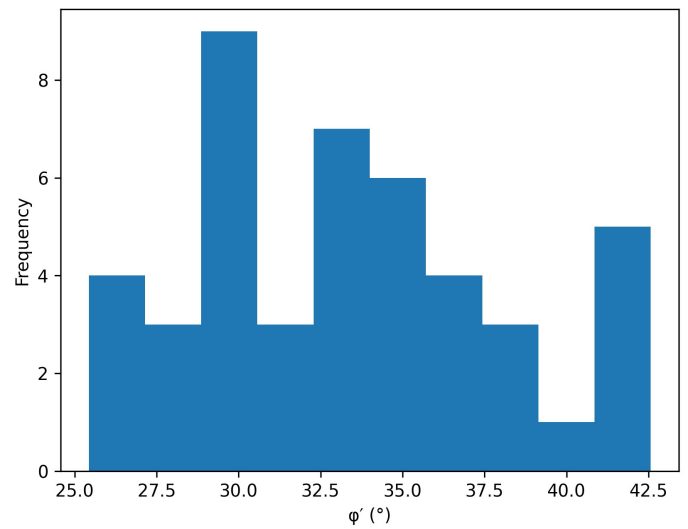


Fig. 8 Frequency distribution of ϕ'

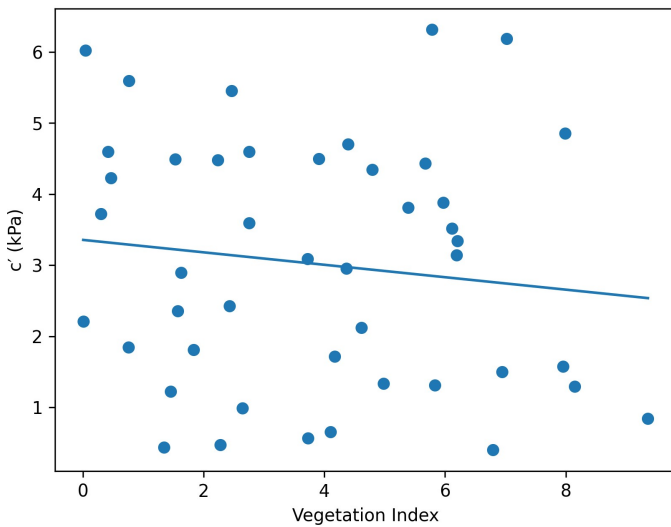


Fig. 6 Relationship between V and c'

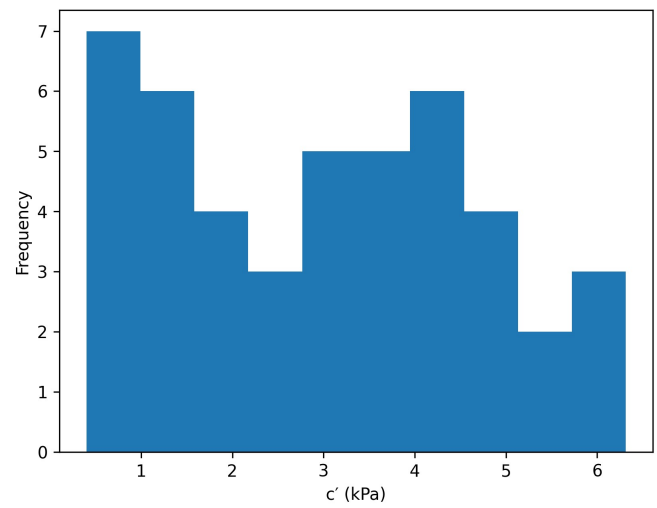


Fig. 9 Frequency distribution of c'

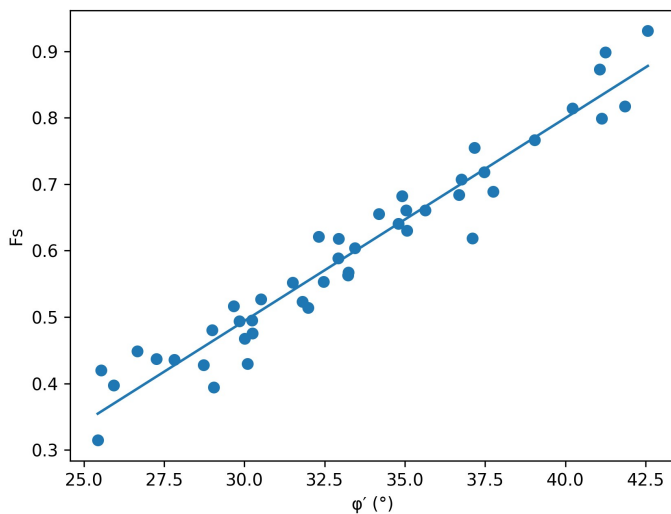


Fig. 7 Relationship between ϕ' and FS

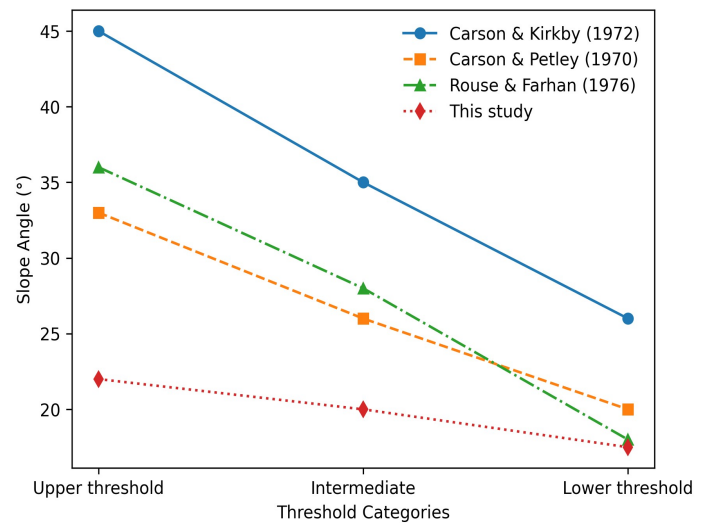


Fig. 10 Comparison of threshold β from this study and previous studies

V. CONCLUSION

This study demonstrates that slope instability in residual and colluvial soils can be effectively predicted using field-derived shear strength parameters obtained from in situ testing. A total of 45 open-sided direct shear box tests conducted across three slope sections (16°, 24°, and 33°) provided a robust dataset for evaluating the mechanical behaviour of slope materials under realistic field conditions. The results show a clear contrast between slope sections: upper and middle slopes, dominated by coarse-grained materials, exhibit higher friction angles ($\phi' = 38.5^\circ\text{--}42.8^\circ$) and low cohesion ($c' = 0\text{--}6.5$ kPa), whereas lower slopes, characterised by finer materials, display reduced friction angles ($\phi' = 25.2^\circ\text{--}29.4^\circ$) and slightly higher cohesion ($c' = 2.0\text{--}4.8$ kPa). Statistical analysis revealed a strong relationship between friction angle and slope gradient ($R^2 = 0.76$), confirming that ϕ' is a primary control on slope stability. In contrast, cohesion showed a moderate correlation with vegetation cover ($R^2 = 0.58$), indicating that root reinforcement contributes locally but is not the dominant stabilising factor. Stability modelling using the infinite slope approach yielded limiting slope angles ranging from 17.2° to 22.4°, closely matching observed shallow failures and previously reported threshold values. The integration of field testing, statistical analysis, and stability modelling highlights that slopes within the range of approximately 19°–23° represent the most critical conditions for instability for weathered regolith and colluvial soils in the study area. These slopes correspond to transitional regolith conditions where reduced frictional resistance and increased pore-water effects combine to lower stability. Overall, the findings confirm that field-based shear strength measurements provide a more realistic representation of heterogeneous slope materials than conventional direct shear strength laboratory methods. The approach offers a reliable and practical framework for slope hazard assessment and engineering decision-making in similar upland environments, particularly where shallow translational failures are dominant.

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DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available from the corresponding author upon reasonable request. No publicly archived dataset was generated.

ETHICS APPROVAL

This study did not involve human participants, personal data, or animal subjects. No specific ethical approval was required.

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AUTHORS' CONTRIBUTIONS

Martin Cross and Sujun Dulal conducted the main data analysis, contributed to the data collection, preprocessing, and interpretation, and were responsible for drafting the initial manuscript. Martin Cross performed supervision, conceptual guidance, conducted critical revision of the manuscript, overall project administration and final approval of the version to be published. All authors read and approved of the final manuscript.

CONFLICT OF INTEREST

The authors have not disclosed any competing interests.

USE OF AI

AI tools were not used in data generation, analysis, results, or decision-making.

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