

Integrated subsurface screening for bioengineering suitability and erosion control on a tropical cut slope

Aimee Halim^{1*} , Muhammad Fahmi Suradi², Normaniza Osman²

¹ Department of Geography, Faculty of Arts and Social Sciences, Universiti Malaya, 50603 Kuala Lumpur, Malaysia

² Institute of Biological Sciences, Faculty of Science, Universiti Malaya, 50603 Kuala Lumpur, Malaysia

* Corresponding author's e-mail: aimeehalim@um.edu.my

ABSTRACT

Tropical cut slopes are highly susceptible to erosion and shallow landslides because intense rainfall interacts with deeply weathered residual soils, yet bioengineering interventions are frequently designed without adequate subsurface characterization. This study aimed to conduct an integrated geological, geophysical, and geotechnical characterization of a tropical cut slope on the Kenny Hill Formation, Selangor, Malaysia, in order to evaluate its suitability for bioengineering. Field reconnaissance and weathering grade classification were combined with a two-dimensional electrical resistivity survey, soil penetration resistance, near-surface moisture content, and erosion rate measurements collected across three vegetation coverage plots over 24 months. The slope was classified as Grade III to IV weathered metasedimentary rock with a sandy clay loam surface texture. Resistivity imaging identified a high resistivity, coarse-textured near-surface layer of 20,000 to 360,000 Ωm at 0 to 5 m depth, overlying a low resistivity, moisture-affected zone of 300 to 800 Ωm at 5 to 14.8 m depth. Penetration resistance increased significantly under vegetation cover, reaching 4.4 kPa in the densely vegetated plot compared with 2.9 kPa in the control, while near-surface moisture content and hydraulic conductivity rose progressively, and erosion rate declined by up to 74.04% relative to the initial condition. These results indicate that the near-surface zone provides mechanically, hydrologically, and ecologically favorable conditions for root establishment, whereas the deeper zone offers limited support for root anchorage. The corresponding reduction in erosion rate confirms that the subsurface conditions identified through this integrated approach translate into measurable improvement in slope performance. Overall, combining weathering grade classification, resistivity zonation, and penetration resistance testing provides a reliable, field-deployable framework for screening tropical cut slopes prior to bioengineering intervention.

Keywords: cut slope, electrical resistivity imaging, penetration resistance, tropical residual soil, slope bioengineering, weathering grade.

INTRODUCTION

Cut slopes are among the landforms most susceptible to failure in humid tropical environments, where intense and prolonged rainfall interacts with deeply weathered residual soils to induce erosion and shallow landslides. In Malaysia, slope failures remain a recurring geohazard despite hills and mountainous terrain occupying less than one quarter of the country's land area. Cut slopes account for the majority of recorded failures, with most failures occurring within the shallow residual soil mantle rather than at

greater depths (Qasim et al., 2013; Rahman and Mapjabil, 2017). Records from the national road authority further indicate that a substantial proportion of cut slopes along federal highways are classified as high risk (JKR, 2009). In addition to topographic and climatic influences, soil-related factors, including parent material, weathering grade, and soil profile depth, consistently control erosion processes and landslide occurrence in Malaysia (Paramanathan et al., 2021). This natural susceptibility is further intensified by anthropogenic activities, particularly slope excavation for infrastructure development, which removes

protective vegetation and accelerates soil detachment. Batumalai et al. (2023) demonstrated that human disturbance on man-made slopes in highland areas significantly increases soil detachment rates, especially during periods of intense rainfall.

The occurrence of cut slope failures cannot be attributed solely to climatic or geological conditions because slope instability results from the complex interaction of geological, hydrological, geotechnical, ecological, and anthropogenic processes (Crozier, 2010). Recent studies further emphasized that the hydrological and mechanical behavior of slopes is governed by coupled hydro-mechanical processes involving rainfall infiltration, vegetation, root reinforcement, soil properties, and groundwater dynamics, rather than by any single controlling factor (Lann et al., 2024). In humid tropical environments, prolonged chemical weathering produces deep residual soil profiles that exhibit considerable spatial variability in strength, permeability, hydraulic conductivity, and structural characteristics, resulting in heterogeneous responses to rainfall infiltration and changes in pore water pressure (Sidle and Ochiai, 2006). During road construction and infrastructure development, slope excavation removes protective vegetation, modifies the original slope geometry, and disrupts natural drainage pathways, thereby altering stress distribution, infiltration patterns, and groundwater movement that collectively increase the susceptibility of slopes to rainfall-induced instability (Highland and Bobrowsky, 2008). These disturbances are particularly critical in tropical residual soils, where the loss of vegetation reduces matric suction and weakens the hydro-mechanical balance that contributes to slope stability (Rahardjo et al., 2007).

As understanding of these coupled processes has advanced, slope stabilization strategies have progressively shifted from conventional structural approaches towards nature-based solutions that integrate ecological and engineering principles. Among these approaches, slope bioengineering has emerged as a sustainable and environmentally compatible technique because vegetation not only reinforces soil mechanically through root development but also regulates infiltration, evapotranspiration, and near-surface hydrological processes (Gray and Sotir, 1996; Tarmidzi et al., 2026). Recent reviews have further demonstrated that the effectiveness of vegetation-based stabilization depends on the interaction between root systems and site-specific geological,

geotechnical, and hydrological conditions, highlighting that successful bioengineering requires a comprehensive understanding of subsurface characteristics before implementation (Lann et al., 2024). Likewise, Stokes et al. (2014) emphasized that effective ecological mitigation of hillslope instability requires integrating vegetation science with geotechnical and hydrological knowledge, rather than treating vegetation establishment as an isolated remedial measure. Consequently, implementing bioengineering without adequate site characterization may substantially reduce its effectiveness, particularly on cut slopes developed within highly weathered and structurally heterogeneous tropical formations.

Slope bioengineering employs living vegetation, either independently or in combination with engineering structures, as the primary means of stabilizing slopes (Albuja-Sánchez et al., 2025). Vegetation contributes to slope stability by reinforcing soil through root systems, reducing surface erosion, and regulating infiltration and evapotranspiration processes. These ecological functions provide a cost-effective and environmentally sustainable alternative, or complement, to conventional structural stabilization methods. Nevertheless, the effectiveness of bioengineering is strongly influenced by local site conditions. Reviews of the bioengineering practice in Malaysia consistently report that the successful implementation of vegetation-based stabilization has been constrained by the limited availability of field-based studies linking subsurface site characteristics with long-term performance outcomes (Dorairaj and Osman, 2021; Mohamed et al., 2023; Tarmidzi et al., 2026). Similarly, Stokes et al. (2014) emphasized that effective ecological mitigation of hillslope instability requires the integration of geotechnical understanding with vegetation science rather than treating vegetation establishment as an isolated remedial measure. Consequently, implementing bioengineering without adequate knowledge of subsurface conditions may substantially reduce its effectiveness, particularly on cut slopes developed within highly weathered and structurally heterogeneous geological formations.

Despite the strong dependence of bioengineering performance on subsurface conditions, site characterization of tropical cut slopes is frequently limited to surface observations that provide only a partial understanding of the underlying geological, geotechnical, and hydrological environment. Surface features alone often fail to

capture subsurface heterogeneity that governs water movement, weathering, root development, and soil mechanical behavior, all of which influence the long-term performance of vegetation-based stabilization (Stokes et al., 2014; Lann et al., 2024). Consequently, comprehensive subsurface investigations are increasingly recognized as an essential prerequisite for selecting and designing appropriate bioengineering interventions. Among the available techniques, electrical resistivity imaging (ERI) has become a widely adopted non-destructive geophysical method because it provides continuous subsurface profiles that reflect variations in moisture content, weathering grade, material texture, and lithology, which are key factors controlling rainfall infiltration and slope stability (Reynolds, 2011; Samouëlian et al., 2005). Studies on tropical residual soils have further demonstrated that ERI effectively delineates saturated, weathered, and relatively competent subsurface zones, with resistivity distributions corresponding closely to geotechnical properties such as cohesion and friction angle (Olabode et al., 2022). Similarly, Kabeta et al. (2023) reported that integrating electrical resistivity tomography with geotechnical testing provided a more reliable assessment of subsurface conditions than either method alone, supporting more effective and site-specific remediation strategies.

While ERI characterizes the spatial distribution of subsurface materials and hydrological conditions, assessment of near-surface soil mechanical properties remains equally important because vegetation establishment depends on the ability of plant roots to penetrate and develop within the soil profile. Soil penetration resistance provides a rapid and reliable in situ measure of soil compaction and mechanical strength, both of which directly influence root growth and root architecture (Bengough et al., 2011). Increasing soil strength restricts root elongation and reduces root proliferation once critical resistance thresholds are exceeded, making penetration resistance a practical indicator of root penetrability and vegetation establishment (Correa et al., 2019). When interpreted together with geological characteristics such as weathering grade, soil texture, and mineralogical composition, penetration resistance complements ERI by providing insight into the mechanical conditions of the root zone. The integration of these geophysical and geotechnical methods, therefore, enables a more comprehensive evaluation of both the hydrological and

mechanical constraints that govern slope suitability for bioengineering intervention.

Although vegetation hydrology interactions on cut slopes have been widely investigated, and both electrical resistivity imaging and soil penetration resistance are well-established methods in geophysical and geotechnical investigations, studies integrating these techniques to evaluate the suitability of tropical cut slopes for bioengineering prior to implementation remain limited. Existing integrated ERI and geotechnical studies have primarily focused on diagnosing landslide hazards, rather than assessing the suitability of sites for vegetation-based stabilization (Kabeta et al., 2023; Olabode et al., 2022). Furthermore, recent reviews of bioengineering practice in Malaysia have identified the lack of field-based and site-specific diagnostic studies as a significant barrier to the wider adoption of bioengineering approaches (Tarmidzi et al., 2026). Consequently, an important practical gap remains in the development of a systematic and field-applicable framework that enables engineers and land managers to evaluate subsurface conditions before selecting and designing an appropriate bioengineering intervention.

To bridge this gap, the present study conducted an integrated geological, geophysical, and geotechnical characterization of a tropical cut slope developed on the Kenny Hill Formation in Selangor, Malaysia (Yin, 2011). The study first characterized the geological setting and weathering grade of the slope before determining its subsurface resistivity structure using electrical resistivity imaging and interpreting the results in relation to material texture and moisture distribution. Near-surface soil penetration resistance was subsequently quantified to evaluate soil mechanical strength and potential constraints to root penetration. Finally, the geological, geophysical, and geotechnical evidence was integrated to assess the suitability of the study slope for bioengineering intervention, thereby providing a scientific basis for informed slope stabilization planning under tropical conditions.

MATERIAL AND METHODS

Study area, geological mapping and weathering classification

The study was conducted on a cut slope along the Guthrie Corridor Expressway (GCE), Selangor, Malaysia (N 03°13'24.1", E 101°30'50.2"),

with a slope gradient of 26–35°. The site receives an annual average precipitation of 2114.5 mm, with air temperature ranging from 25 to 33 °C and relative humidity of 60–75%. Field reconnaissance and geological mapping were carried out to identify the formation underlying the study area. The weathering grade was classified following the scheme of the International Society for Rock Mechanics (Brown, 1981; Azlan et al., 2025).

Experimental plots and revegetation treatment

Three 8 × 8 m plots were established under a completely randomized design representing bare (control, 0% coverage), less dense (50% coverage), and dense (80% coverage) vegetation, planted with *Lantana camara*, *Melastoma malabathricum*, and *Bauhinia purpurea* using a Microclimate Plant Propagation Technique. Full details of plot layout, species selection, and planting protocol are reported in the companion study (Halim et al., 2021).

Soil morphology and physicochemical properties

Soil particle size distribution was determined through mechanical analysis following American Society for Testing and Materials (ASTM) D6913/D6913M-17, where air-dried soil samples were sieved using a series of sieves (2.0, 1.0, 0.5, 0.25, 0.1, and 0.05 mm). The obtained particle size fractions were used to classify soil texture according to the USDA soil texture classification system (ASTM, 2017; Soil Survey Staff, 2017). Mineral composition was determined by X-ray diffraction (XRD; EMPYREAN, Malvern Panalytical, UK) using Ni-filtered Cu-K α radiation (10 mA, 45 kV), scanning between 2° and 70° (2 θ) at 8.00°/min. Chemical composition was determined by X-ray fluorescence spectrometry (XRF; Axios FAST, PANalytical, Netherlands) following fusion-bead preparation, with major elements expressed as oxides (Yamasaki et al., 2023). Then, soil pH was measured on the same samples. The in situ soil moisture content was measured at a depth of 5 cm using a portable soil moisture meter (HH2 Moisture Meter, Delta-T Devices Ltd., England), recorded between 1130 and 1230 h to coincide with the timing of the electrical resistivity survey.

Electrical resistivity survey

A two-dimensional electrical resistivity survey was conducted using a resistivity meter (SAS4000, ABEM Instrument AB, Sweden) with an electrode selector system (LUND ES464, ABEM Instrument AB, Sweden). A Schlumberger array was deployed along an 80 m survey line at the base of the slope with 2 m electrode spacing, energized by a 12 V direct-current source. Measurements were taken between 11:30 and 12:30 and repeated three times; the inversion model was generated using RES2D-INV software (McKenzie et al., 2004).

Soil penetration resistance

Soil penetration resistance was measured in situ every six months over 24 months using a portable penetrometer with a 60° cone (Eijkelkamp Agrisearch Equipment, model 06.15, The Netherlands), pushed vertically into the soil and recorded in kilopascals (kPa). Measurements were taken from seven randomly selected points per plot, following a zigzag traverse.

Erosion rate

Soil erosion rate was determined using Gerlach troughs, where this method remains widely applied in recent tropical erosion studies (Gerlach, 1967; Wicharuck et al., 2023). Each experimental plot was enclosed with a wooden barrier 25 cm in height, and eroded sediment was collected from three positions, namely the collection tank, sediment deposited against the wooden barrier near the outlet, and sediment retained within the outlet PVC pipe. Collected sediment was air-dried and weighed, and the erosion rate was expressed in tonnes per hectare per year (t ha⁻¹ yr⁻¹). Erosion severity was classified according to the Department of Environment Malaysia guidelines (Department of Environment, 2003; Mir et al., 2010).

Statistical analysis

One-way analysis of variance (ANOVA) was used to test the effect of vegetation coverage on penetration resistance, with least significant difference (LSD) post-hoc comparisons at $p \leq 0.05$, using SPSS software (version 20, IBM, USA). Pearson correlation analysis was used to examine the relationship between penetration resistance and the depth-averaged resistivity values extracted

from the corresponding zones of the inverted resistivity model, in order to assess the degree of agreement between the geophysical and geotechnical datasets prior to their joint interpretation.

RESULTS

Regional geology and weathering grade of the study site

Field reconnaissance identified the study area as being underlain by the Kenny Hill Formation (Figure 1), which comprises low-grade metasedimentary rocks predominantly consisting of inter-bedded sandstone and shale that have undergone metamorphism to form quartzite and phyllite. This geological formation is characterized by poor fossil content and is assigned a Carboniferous to Permian age (Lee, 2001; Mohamed et al., 2007; Yin, 2011). Based on the classification scheme proposed by the International Society for Rock Mechanics (Brown, 1981; Azlan et al., 2025), the weathering grade of the study area was classified as Grade III to Grade IV, representing partially to highly weathered materials with mixed ground characteristics and partially decomposed rock mass.

Soil textural class, mineralogy, and chemical composition

The uppermost layer of the cut slope is characterized by a thin O/A horizon consisting of

decomposed organic litter and surface mineral materials. The underlying layer is predominantly represented by the C horizon, which comprises sediment, saprolite, bedrock, and other geological materials that range from partially to highly weathered. Based on particle size distribution, the weathered surface materials were classified as sandy clay loam (Figure 2).

The X-ray diffraction (XRD) analysis (Figure 3) identified quartz as the dominant mineral in the study area. The soil was primarily composed of silicon oxide (SiO_2) and aluminum oxide (Al_2O_3), accounting for 62.7% and 15.2% of the chemical composition, respectively, with soil pH ranging from 3.78 to 5.37, indicating moderately to slightly acidic conditions. Under acidic conditions, aluminum is solubilized into phytotoxic Al^{3+} , reducing nutrient availability and inhibiting plant growth (Bojórquez-Quintal et al., 2017; Rahman et al., 2018). Consequently, the soil can be classified as infertile (Osman, 2012), which may hinder vegetation establishment and increase susceptibility to soil erosion. Rill and gully erosion features were observed in the field, consistent with this baseline soil condition (Figure 4).

2D resistivity inversion model – depth-stratified resistivity zones and interpretation of subsurface heterogeneity

The inverted resistivity model revealed a wide range of resistivity values, indicating heterogeneous subsurface conditions within

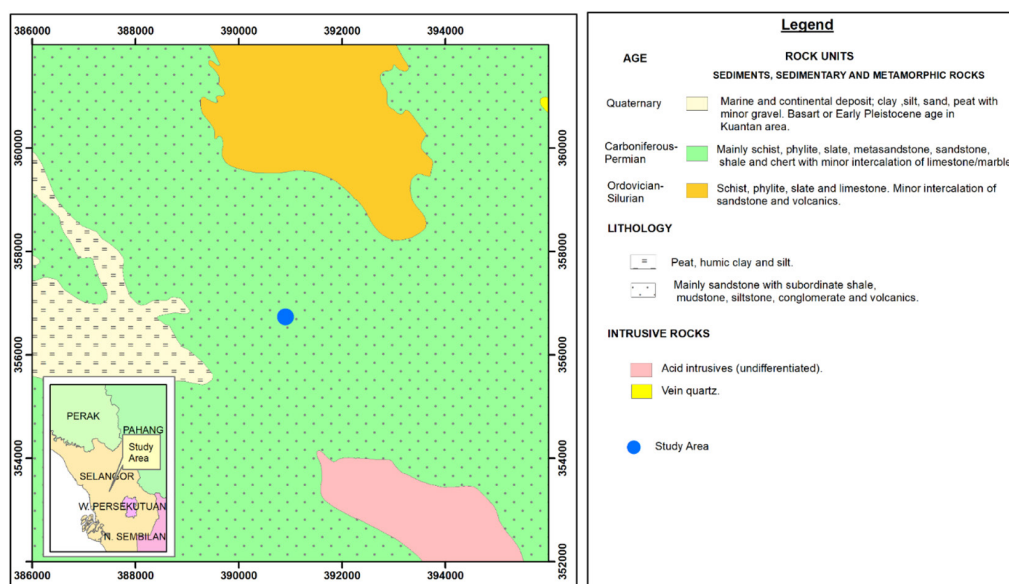


Figure 1. Geological map of the study area; the blue circle marks the location of the study

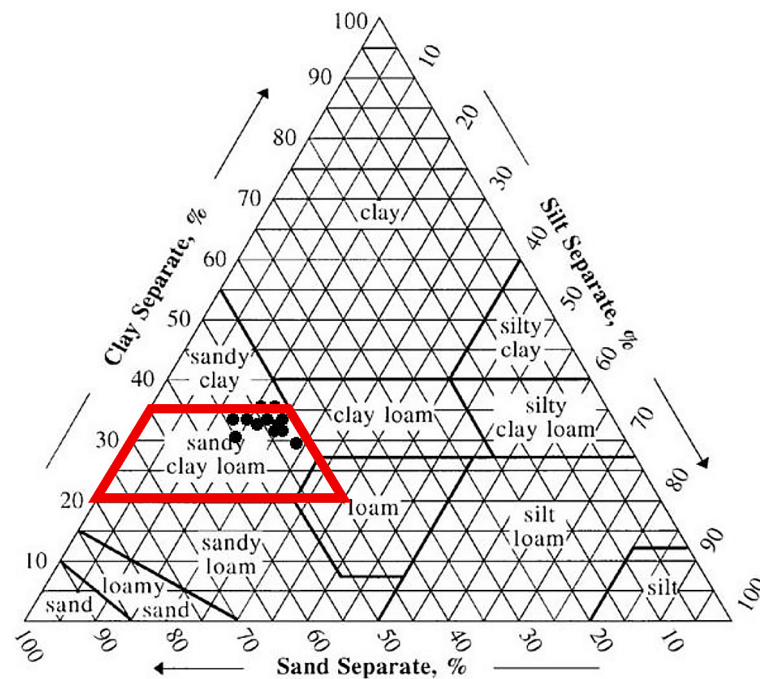


Figure 2. Soil texture classification – distributions of the subsurface soil textural class in the study area (black dot); soil texture triangle based on the USDA particle-size classification

the study area (Figure 5). The upper soil layer (0–5 m depth) exhibited relatively high resistivity values ranging from 20,000 to 360,000 Ωm , suggesting the predominance of coarse-textured sandy clay loam, which limits the propagation of electrical current through the soil. This observation is consistent with the findings of Abidin et al. (2012, 2017), who reported that coarse-grained soils, such as sand, generally exhibit

higher resistivity values than finer-grained materials. In contrast, the lower subsurface layer (5–14.8 m depth) showed comparatively lower resistivity values ranging from 300 to 800 Ωm , indicating the presence of relatively weak and moisture-rich zones. This interpretation is supported by previous studies demonstrating that electrical resistivity is strongly influenced by soil moisture content (Ozcep et al., 2010; Siddiqui and Osman, 2012). Although the interpretation of resistivity data may involve some degree of uncertainty, the identification of low resistivity zones provides an important early indication of potentially unstable subsurface conditions. Such highly conductive zones may represent areas susceptible to slope instability and could increase the likelihood of failure during periods of prolonged or intense rainfall (Abidin et al., 2012; Hussin et al., 2017).

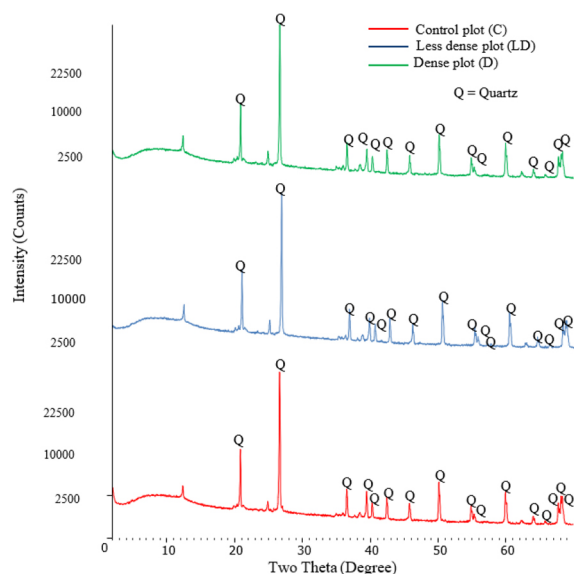


Figure 3. XRD graphs of the three experimental plots of soil at various 2θ angles

Baseline geological and geophysical characteristics

Table 1 summarizes the baseline geological, mineralogical, chemical, and geophysical characteristics of the study slope, providing a reference dataset against which the vegetation-soil findings of the companion papers can be interpreted (Halim et al., 2021; Normaniza et al., 2018).



Figure 4. Rill and gully erosions observed at the study area

Soil moisture content in the near-surface rooting zone

To provide an independent, ground-truthed check on the hydrological interpretation of the near-surface resistivity zone, in situ soil moisture content was monitored at 5 cm depth alongside penetration resistance over the same 24-month period (Figure 6). Moisture content remained comparable across all plots during the first 12 months, consistent with rainfall being the dominant control on near-surface moisture during this period, rather than vegetation cover. From month 12 onward, however, the moisture content

increased progressively in the vegetated plots, reaching a 69.31% increase in the dense plot and a 32.00% increase in the less dense plot, while the control plot showed no consistent increase. The dense plot recorded moisture content values 27.44% and 68.37% higher than the less dense and control plots, respectively, by the end of the study. This vegetation-driven increase in near-surface moisture retention was accompanied by a corresponding rise in soil hydraulic conductivity, which increased by 73.80% in the dense plot and 30.85% in the less dense plot relative to the control. Because these measurements were confined to the near surface interval corresponding to the high resistivity zone identified in the resistivity model (0 to 5 m depth), they do not directly verify the moisture condition of the deeper, low resistivity zone (5 to 14.8 m depth); however, they confirm that the near surface rooting zone becomes progressively wetter and more hydraulically conductive under vegetation cover, supporting its interpretation as a hydrologically, as well as mechanically, favorable rooting horizon for bioengineering vegetation.

Soil penetration resistance profile and its spatial variability

Penetration resistance values across the three sampling plots, namely the control (bare), less dense (LD), and dense (D) vegetation cover, were comparable at the beginning of the monitoring period, indicating relatively uniform near-surface soil compaction across the slope prior to vegetation establishment (Figure 7). Over the monitoring period, however, penetration resistance diverged

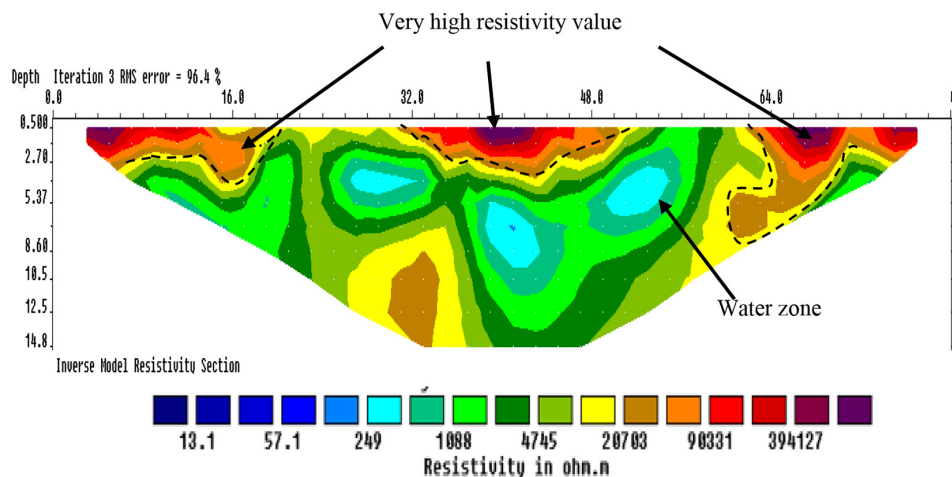


Figure 5. 2D inversion model resistivity of the study area

Table 1. Summary of baseline geological, mineralogical, chemical and geophysical characteristics of the study slope

Parameter	Value
Geological formation	Kenny Hill Formation (interbedded meta-sandstone and phyllite)
Weathering grade (ISRM)	III–IV (partially to highly weathered)
Surface soil texture	Sandy clay loam
Dominant mineral (XRD)	Quartz
SiO ₂ content (XRF)	62.7%
Al ₂ O ₃ content (XRF)	15.2%
Soil pH	3.78–5.37 (moderately to slightly acidic)
Shallow resistivity zone (0–5 m depth)	20,000–360,000 Ω·m
Deep resistivity zone (5–14.8 m depth)	300–800 Ω·m (interpreted moisture-rich weak zone)

markedly among the plots, with the dense vegetation plot recording the highest value (4.4 kPa) and the control plot the lowest (2.9 kPa). Relative to the initial condition, penetration resistance increased by 51.72% in the dense plot and 24.14% in the less dense plot, whereas no comparable increase was observed in the control plot. This divergence became statistically significant from month 18 onward ($p \leq 0.05$), coinciding with the period of most pronounced separation between the vegetated and unvegetated plots. This progressive divergence suggests that soil mechanical properties evolved in response to vegetation development rather than representing an inherent characteristic of the slope, consistent with root-soil bonding through rhizosphere development (Helliwell et al., 2019).

This interpretation is further supported by recent modeling studies demonstrating that the spatial variability of root architecture and soil properties is a primary control on the mechanical

behavior of vegetated slopes. Using a random field approach, Guo et al. (2024) showed that heterogeneity in root distribution and orientation significantly influences slope reliability under rainfall infiltration. Accordingly, the higher penetration resistance observed in densely vegetated areas is likely to represent localized root induced reinforcement rather than measurement variability. These findings highlight the importance of incorporating vegetation driven mechanical heterogeneity into the assessment of cut slope suitability for bioengineering interventions.

Erosion rate response to vegetation cover

Erosion rate, measured using Gerlach troughs over the 24-month study period, declined progressively in both vegetated plots relative to the control (Figure 8). At the beginning of the experiment, the erosion rate of the study slope was classified as low to moderately low according to the Department of

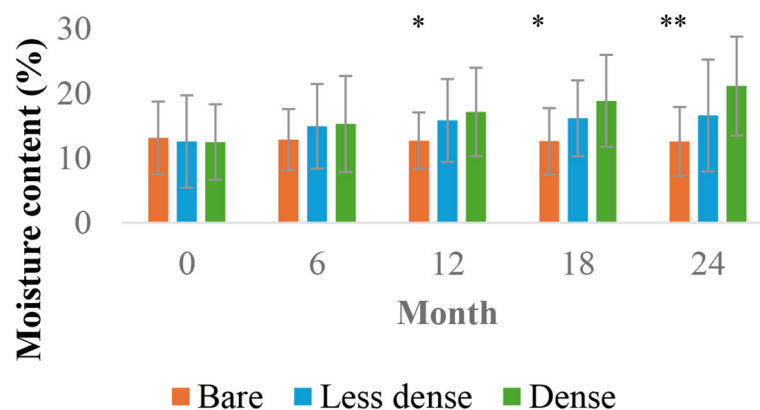


Figure 6. Mean of moisture content for the three experimental plots at varying vegetation coverages; vertical bars indicate the standard deviation, while * and ** denote significant differences at $p \leq 0.05$ and $p \leq 0.001$, respectively

Environment Malaysia erosion classification (Department of Environment, 2003). By the end of the study, the erosion rate had decreased by 74.04% in the dense plot and 50.10% in the less dense plot, whereas the control plot exhibited a fluctuating trend attributed primarily to variation in rainfall events rather than a consistent temporal decline. At the end of the study, the dense plot recorded a significantly lower erosion rate than the less dense and control plots, by 47.6% and 76.17% respectively, and the vegetated plots were reclassified as low and very low erosion severity, corresponding to an estimated reduction of 10 to 15 t ha⁻¹ yr⁻¹ in total soil loss.

This outcome directly links the subsurface suitability of the near-surface zone, identified through resistivity zonation, penetration resistance, and moisture content, to a measurable reduction in surface erosion, providing field evidence that the integrated screening framework proposed in this study corresponds to an actual improvement in slope performance rather than a purely diagnostic exercise.

Integrated interpretation of resistivity zonation, penetration resistance, and weathering-textural data: Toward a bioengineering suitability framework

Considered individually, the geological, geophysical, and geotechnical datasets each describe a different aspect of the study slope; considered together, they provide a coherent interpretation of the subsurface conditions. Field reconnaissance classified the slope as Kenny Hill Formation metasedimentary rock with a weathering

grade of III to IV, representing partially to highly weathered materials exhibiting mixed soil-rock behavior. The surface horizon was texturally classified as sandy clay loam dominated by quartz, which corresponds closely with the resistivity structure recovered from the 2D inversion model. The near-surface interval (0–5 m depth) exhibited high resistivity values of 20,000–360,000 Ω m, consistent with the coarse-textured sandy clay loam, where the sand fraction restricts electrical current flow, as reported by Abidin et al. (2012, 2017). In contrast, the deeper interval (5–14.8 m) exhibited markedly lower resistivity values of 300–800 Ω m, indicating a moisture-affected weak zone that is consistent with the Grade III–IV weathering observed in the field and previous studies linking low resistivity to elevated moisture content and weaker geotechnical conditions (Ozcep et al., 2010; Siddiqui and Osman, 2012).

The penetration resistance data provide an independent line of evidence supporting this subsurface zonation. Measurements were confined to the near-surface interval (Zone 1), where penetration resistance increased over time in the vegetated plots, particularly in the dense vegetation plot (51.72%), whereas no comparable increase was observed in the control plot. This trend is consistent with root-induced strengthening of the coarse-textured surface layer through root-soil interaction (Helliwell et al., 2019). Although penetration resistance was not measured within the deeper low resistivity zone, the combined evidence of low resistivity, advanced weathering, and elevated moisture content suggests that this interval provides limited mechanical support for root anchorage and is more appropriately interpreted as a potential zone of

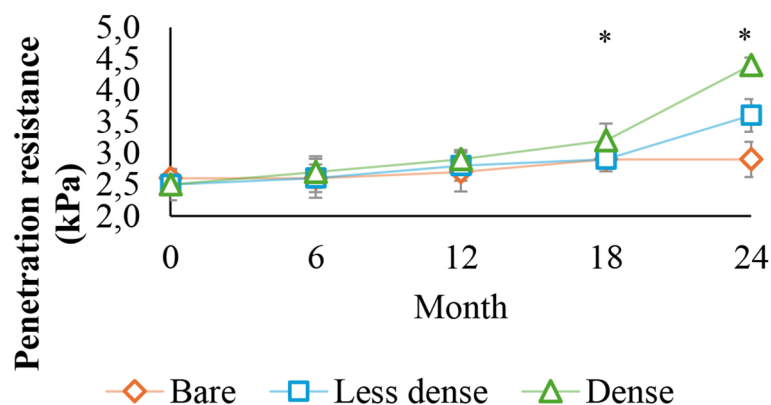


Figure 7. Mean of penetration resistance value for the three experimental plots at varying vegetation coverages; vertical bars indicate the standard deviation, while * and ** denote significant differences at $p \leq 0.05$ and $p \leq 0.001$, respectively

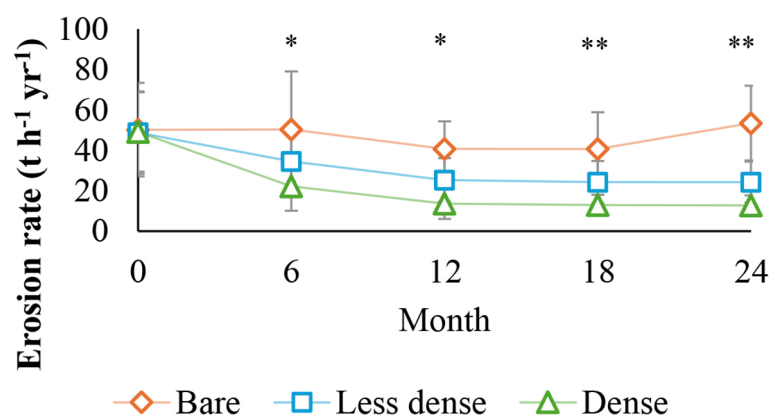


Figure 8. Mean of erosion rate for the three experimental plots at varying vegetation coverages; vertical bars indicate the standard deviation, while * and ** denote significant differences at $p \leq 0.05$ and $p \leq 0.001$, respectively

instability than a suitable rooting horizon for bio-engineering. Table 2 summarizes the integrated interpretation of the geological, geophysical, and geotechnical datasets into a practical framework for assessing slope suitability.

This cross-method agreement supports recent findings that integrating electrical resistivity with geotechnical information provides a more reliable characterization of subsurface conditions than either method alone. Raza et al. (2025) similarly combined electrical resistivity tomography with geological and hydrological evidence to demonstrate that moisture-induced weakening within low resistivity zones was the principal control on slope instability. Collectively, these findings indicate that integrating resistivity zonation, weathering grade, and near-surface penetration resistance provides a practical, field-deployable approach for evaluating the rooting zone of tropical cut slopes, identifying areas favorable for vegetation establishment while highlighting subsurface conditions that may limit the effectiveness of bio-engineering interventions.

DISCUSSION

Resistivity contrasts and slope failure susceptibility

The two-zone resistivity structure identified on the study slope, comprising a high resistivity, coarse-grained near-surface layer (20,000–360,000 Ωm ; 0–5 m) overlying a low resistivity, moisture-affected zone (300–800 Ωm ; 5–14.8 m), corresponds to the subsurface conditions

most commonly associated with tropical cut slope failure. Elevated moisture content within the deeper weathered zone reduces the effective strength of residual soils, and the combined effects of advanced weathering and moisture ingress have been consistently recognized as key factors contributing to landslide occurrence in Malaysia (Qasim et al., 2013; Rahman and Mapjabil, 2017; Paramanathan et al., 2021). The close correspondence between the low resistivity zone and the Grade III–IV weathering condition observed during field reconnaissance further supports the interpretation that these anomalies represent moisture weakened zones with elevated failure susceptibility, consistent with previous resistivity-based investigations (Abidin et al., 2012, 2017; Ozcep et al., 2010; Siddiqui and Osman, 2012; Hussin et al., 2017).

Penetration resistance as an indicator of root-penetrability and compaction

Penetration resistance responded to vegetation cover in a manner directly relevant to bio-engineering performance, rather than slope stability alone. Resistance increased over time beneath the vegetated plots, particularly in the densely vegetated plot, with the divergence from the control becoming statistically significant from month 18 onward, whereas no comparable increase was observed in the unvegetated control. This pattern is consistent with root-induced strengthening of the rhizosphere, whereby root development enhances soil cohesion through root-soil interaction (Helliwell et al., 2019). Although excessive soil strength can restrict root elongation and delay

Table 2. Integrated subsurface suitability framework combining resistivity zonation, weathering grade, and penetration resistance response

Subsurface zone	Zone 1: Near-surface (0–5 m)	Zone 2: Deeper subsurface (5–14.8 m)
Resistivity (Ωm)	20,000–360,000 (high)	300–800 (low)
Weathering grade	Grade III (partially weathered)	Grade III–IV (highly weathered)
Penetration resistance response	Increased under vegetation (up to 4.4 kPa in the densely vegetated plot)	Not directly measured; inferred low strength
Bioengineering interpretation	Coarse, sandy clay loam matrix; mechanically responsive to root establishment, suitable rooting zone for shallow-to-moderate-rooted bioengineering species	Moisture-affected, mechanically weak zone; limited value as a primary rooting target, may require complementary structural support rather than vegetation alone

root development (Correa et al., 2019), the concentration of increased penetration resistance within the coarse-textured, high-resistivity near-surface layer indicates that this zone remains mechanically favorable for root establishment rather than acting as a compaction barrier. This interpretation is further supported by Guo et al. (2024), who demonstrated that spatial heterogeneity in root and soil properties is a primary control on the mechanical behavior of vegetated slopes, suggesting that the vegetation-associated increase in penetration resistance observed in this study reflects meaningful root reinforcement rather than random spatial variability. The delayed onset of statistical significance also indicates that root-driven mechanical reinforcement in this substrate develops gradually, becoming detectable only after approximately a year and a half of vegetation establishment, a consideration relevant to the timeframe over which bioengineering performance should be evaluated in similar tropical residual soils.

Hydrological validation of the near-surface rooting zone

The near-surface moisture content and hydraulic conductivity data provide an independent, hydrologically grounded complement to the mechanical evidence discussed above. Moisture content and hydraulic conductivity remained comparable across all plots during the first year, indicating that rainfall, rather than vegetation cover, was the dominant control on near-surface hydrology during early establishment. From month 12 onward, however, both parameters increased progressively in the vegetated plots, most markedly in the densely vegetated plot, consistent with vegetation-mediated improvements in soil structure, macropore development, and infiltration capacity.

Because these measurements were confined to the near surface interval corresponding to the high resistivity zone identified geophysically, they do not directly confirm the moisture condition of the deeper, low resistivity zone; rather, they demonstrate that the near surface rooting zone itself becomes progressively wetter and more conductive as vegetation establishes, indicating that this zone is not only mechanically but also hydrologically favorable for sustaining root growth over time. This finding adds an additional, independently measured line of evidence to the integrated suitability framework proposed in this study, alongside the resistivity, weathering, and penetration resistance data already discussed.

Erosion outcomes as validation of the suitability framework

The decline in erosion rate observed in the vegetated plots provides a direct, field-measured outcome that closely tracks the subsurface suitability pattern identified through resistivity zonation, penetration resistance, and moisture content. Erosion rate decreased by 74.04% in the densely vegetated plot and 50.10% in the less dense plot over the study period, while the control plot showed no consistent decline, and the slope was reclassified from a low to moderately low erosion category to a low or very low category by the end of the study (Department of Environment, 1996). This outcome is consistent with the well-established role of root systems in enhancing soil resistance to detachment and surface runoff, primarily through increased soil aggregate stability and greater energy required to dislodge root-bound particles (Gyssels et al., 2005). Importantly, this erosion reduction occurred specifically in the same near-surface zone identified as mechanically and hydrologically favorable for

root establishment, indicating that the integrated screening framework proposed in this study is not merely diagnostic but corresponds to a measurable improvement in slope performance. This strengthens the practical case for applying resistivity, penetration resistance, and moisture-based screening before bioengineering implementation, since the subsurface conditions favorable for root establishment identified through this framework translated directly into reduced soil loss under field conditions.

Integrating geophysical and geotechnical evidence for bioengineering suitability

Taken individually, weathering grade, resistivity, and penetration resistance each provide only a partial understanding of the slope; when integrated, they converge on a coherent assessment of subsurface suitability for bioengineering. The near-surface zone, characterized by Grade III weathering, high resistivity, coarse-textured material, and increasing penetration resistance, provides favorable conditions for root establishment and can therefore serve as the primary rooting horizon for bioengineering vegetation. This interpretation is consistent with the principle that successful bioengineering depends on the compatibility between root architecture and the physical properties of the substrate (Gray and Sotir, 1996; Tarmidzi et al., 2026). In contrast, the deeper Grade III–IV, low resistivity, moisture-affected zone is unlikely to provide comparable mechanical support because it lies largely beyond the effective rooting depth of most early successional bioengineering species. This finding further supports the recommendation that bioengineering design should be based on site-specific geotechnical characterization rather than applied as a generic stabilization approach (Stokes et al., 2014).

Practical implications for site screening

For practitioners, the value of this integrated approach lies in its simplicity and field applicability. A resistivity survey, portable penetrometer, and weathering grade assessment can be conducted rapidly without laboratory analysis, providing a practical means of identifying the zones favorable for root establishment as well as subsurface conditions that may limit bioengineering performance. This directly addresses the gap identified in recent reviews of Malaysian bioengineering

practice, which highlight the shortage of field-based, site-specific diagnostic studies as a constraint to the wider adoption of vegetation-based slope stabilization (Tarmidzi et al., 2026). Incorporating this pre-treatment subsurface screening approach into routine site investigations, alongside existing practices such as the national slope classification framework (JKR, 2009), would enable practitioners to select suitable bioengineering species and optimize design based on subsurface conditions rather than relying solely on surface observations (Dorairaj and Osman, 2021; Mohamed et al., 2023).

Comparison with other tropical and humid-region studies

The pattern identified on this slope is consistent with and reinforced by comparable integrated geophysical and geotechnical studies elsewhere. Olabode et al. (2022) similarly found that resistivity zonation in a residual soil slope corresponded closely with independently measured geotechnical strength parameters, while Kabeta et al. (2023) demonstrated that combining electrical resistivity tomography with geotechnical testing provided a more comprehensive assessment of subsurface conditions than either method alone. More recently, Raza et al. (2025) applied an integrated geophysical and geotechnical approach to slope instability assessment and likewise identified moisture-induced weakening and low resistivity zones as the principal controls on subsurface instability, closely mirroring the zonation observed in the present study. Collectively, these findings suggest that the relationship between resistivity, penetration resistance, and weathering characteristics identified in this study is not unique to the investigated slope but represents a broader pattern across weathered tropical residual soils. This supports the use of integrated geological, geophysical, and geotechnical characterization as a practical and reliable basis for evaluating slope suitability prior to bioengineering intervention.

Limitations

Several limitations should be considered when interpreting these findings. The resistivity survey was conducted along a single 80 m line at one point in time, and repeated only within a single day (1130 to 1230 h); it therefore captures a single moisture snapshot rather than seasonal

variation, and cannot rule out changes in the resistivity structure between the wet and dry seasons. Penetration resistance and near-surface moisture content measurements were confined to the near-surface zone and were not obtained at the depths sampled by the resistivity survey, so the mechanical and hydrological characterization of the deeper, low-resistivity zone remains inferential rather than directly measured. Similarly, erosion rate reflects the combined influence of rainfall variability and vegetation cover rather than resistivity or penetration resistance alone, and should be interpreted as a corroborating outcome rather than direct proof of the proposed subsurface suitability mechanism. Finally, as the study was conducted on a single cut slope within the Kenny Hill Formation, the specific resistivity, penetration resistance, moisture, and erosion thresholds identified here may not transfer directly to slopes of different lithology, and should be treated as a demonstration of an integrated screening approach, rather than as universal suitability thresholds.

CONCLUSIONS

This study characterized a tropical cut slope developed on the Kenny Hill Formation using an integrated geological, geophysical, and geotechnical approach to evaluate its suitability for bioengineering intervention. The slope was classified as Grade III to IV weathered metasedimentary rock with a sandy clay loam surface texture, and electrical resistivity imaging revealed two distinct subsurface zones, namely a high resistivity, coarse-textured near-surface layer and an underlying low resistivity, moisture-affected zone at greater depth. Penetration resistance within the near-surface layer increased significantly under vegetation cover, with the divergence between vegetated and unvegetated conditions becoming statistically significant over time, consistent with root-induced strengthening through root-soil interaction. This mechanical response was accompanied by a progressive increase in near-surface moisture content and hydraulic conductivity under vegetation, together with a marked decline in erosion rate that reclassified the slope from a higher to a lower erosion severity category over the study period.

Taken together, these findings indicate that the near-surface zone offers mechanically, hydrologically, and ecologically favorable

conditions for root establishment, whereas the deeper, moisture-affected zone represents a relatively weak layer with limited capacity to support root anchorage. The study slope is therefore considered suitable for bioengineering intervention within its near-surface horizon, provided that species selection and design account for the weaker conditions persisting at depth. The accompanying reduction in erosion rate confirms that the subsurface conditions identified through this integrated characterization translate into a measurable improvement in slope performance, demonstrating that combining weathering grade classification, resistivity zonation, and penetration resistance testing provides a reliable basis for assessing the suitability of tropical cut slopes for bioengineering intervention.

Acknowledgement

This work was supported by the Universiti Malaya Research Grant (UMRG-RP005A-13SUS and RP005D-13SUS) and the Universiti Malaya Grant (UMG020J-2024). The authors thank the Guthrie Corridor Expressway (GCE) for the use of their slope as the study site, and the Ministry of Higher Education Malaysia for scholarship support (MyBrain15).

REFERENCES

1. Abidin, Z., Hazreek, M., Saad, R., Fauziah, A., Wijeyesekera, C., Baharuddin, T., Faizal, M. (2012). Integral analysis of geoelectrical (resistivity) and geotechnical (SPT) data in slope stability assessment. *Academic Journal of Science*, 1(2), 305–316.
2. Abidin, M. H. Z., Madun, A., Tajudin, S. A. A., Baharuddin, M. F. T., Yusof, M. F., Zakaria, M. N., Rahmat, S. N. (2017). Evaluation of unknown tube well depth using electrical resistivity method. *MATEC Web of Conferences*, 103, Article 07002. <https://doi.org/10.1051/mateconf/201710307002>
3. Albuja-Sánchez, J., Solano-Vinueza, G., Damián-Chalán, A. (2025). Bioengineering of soils for ground improvement and stability: A review of nature-based technologies. *Environmental Challenges*, 20, Article 101293. <https://doi.org/10.1016/j.envc.2025.101293>
4. American Society for Testing and Materials. (2017). *ASTM D6913/D6913M-17: Standard test methods for particle-size distribution (gradation) of soils using sieve analysis*. ASTM International. https://doi.org/10.1520/D6913_D6913M-17

5. Azlan, M. F. M. D., Mohamad, E. T., Komoo, I., Madun, A., Muztaza, N. M., Taib, A. M., Suparman-to, E. K., Ibrahim, A., Abang Hasbollah, D. Z., Abu Talib, M. K. (2025). Classification of heterogeneous granitic weathering in tropical regions: Influence of weathering zones, joints, and boulder occurrences via statistical analysis. *Environmental Science and Pollution Research*. <https://doi.org/10.1007/s11356-025-36936-w>
6. Baturalai, P., Mohd Nazer, N. S., Simon, N., Sulaiman, N., Umor, M. R., Ghazali, M. A. (2023). Soil detachment rate of a rainfall-induced landslide soil. *Water*, 15(12), 2149. <https://doi.org/10.3390/w15122149>
7. Bengough, A. G., McKenzie, B. M., Hallett, P. D., Valentine, T. A. (2011). Root elongation, water stress, and mechanical impedance: A review of limiting stresses and beneficial root tip traits. *Journal of Experimental Botany*, 62(1), 59–68. <https://doi.org/10.1093/jxb/erq350>
8. Bojórquez-Quintal, E., Escalante-Magaña, C., Echevarría-Machado, I., Martínez-Estévez, M. (2017). Aluminum, a friend or foe of higher plants in acid soils. *Frontiers in Plant Science*, 8, Article 1767. <https://doi.org/10.3389/fpls.2017.01767>
9. Brown, E. T. (Ed.). (1981). *Rock characterization testing and monitoring: ISRM suggested methods*. Pergamon Press.
10. Correa, J., Postma, J. A., Watt, M., Wojciechowski, T. (2019). Soil compaction and the architectural plasticity of root systems. *Journal of Experimental Botany*, 70(21), 6019–6034. <https://doi.org/10.1093/jxb/erz383>
11. Crozier, M. J. (2010). Deciphering the effect of climate change on landslide activity: A review. *Geomorphology*, 124(3–4), 260–267. <https://doi.org/10.1016/j.geomorph.2010.04.009>
12. Department of Environment. (2003). *Environmental Impact Assessment for Agriculture, Department of Environment*, Ministry of Science, Technology and Environment, Malaysia.
13. Dorairaj, D., Osman, N. (2021). Present practices and emerging opportunities in bioengineering for slope stabilization in Malaysia: An overview. *PeerJ*, 9, e10477. <https://doi.org/10.7717/peerj.10477>
14. Gerlach, T. (1967). Hillslope troughs for measuring sediment movement. *Revue de Géomorphologie Dynamique*, 17, 173–175.
15. Gray, D. H., Sotir, R. B. (1996). *Biotechnical and soil bioengineering slope stabilization: A practical guide for erosion control*. John Wiley & Sons.
16. Gyssels, G., Poesen, J., Bochet, E., Li, Y. (2005). Impact of plant roots on the resistance of soils to erosion by water: a review. *Progress in Physical Geography*, 29(2), 189–217. <https://doi.org/10.1191/030913305pp443ra>
17. Guo, H., Qu, C., Liu, L., Zhang, Q., Liu, Y. (2024). Reliability analysis of vegetated slope considering spatial variability of soil and root properties. *Computers and Geotechnics*, 169, 106257. <https://doi.org/10.1016/j.compgeo.2024.106257>
18. Halim, A., Yusoff, I., Osman, N., Mohamed, N. A. (2021). Delineating the dynamic interaction of vegetation and soil properties in controlling cut slope soil erosion. *Applied Ecology and Environmental Research*, 19(4), 2761–2778. https://doi.org/10.15666/aeer/1904_27612778
19. Helliwell, J. R., Sturrock, C. J., Miller, A. J., Whalley, W. R., Mooney, S. J. (2019). The role of plant species and soil condition in the physical development of the rhizosphere. *Plant, Cell & Environment*, 42(6), 1974–1986. <https://doi.org/10.1111/pce.13529>
20. Highland, L. M., Bobrowsky, P. (2008). *The landslide handbook: A guide to understanding landslides* (U.S. Geological Survey Circular 1325). U.S. Geological Survey. <https://pubs.usgs.gov/circ/1325/>
21. Hussin, H., Ariffin, M. H., Sulaiman, M. A. A., Fauzi, N. (2017). Effectiveness of 2-D resistivity survey to identify lineament (fault) from photolineament interpretation: Case study at Kampung Dato' Mufti, Ampang, Selangor. *Journal of Tropical Resources and Sustainable Science*, 5, 1–8. <https://doi.org/10.47253/jtrss.v5i1.380>
22. Jabatan Kerja Raya (JKR) Malaysia. (2009). *National Slope Master Plan 2009–2023*. Public Works Department Malaysia.
23. Kabeta, W. F., Tamiru, M., Tsige, D., Ware, H. (2023). An integrated geotechnical and geophysical investigation of landslide in Chira town, Ethiopia. *Heliyon*, 9(7), e17620. <https://doi.org/10.1016/j.heliyon.2023.e17620>
24. Lann, T., Bao, H., Lan, H., Zheng, H., Yan, C., Peng, J. (2024). Hydro-mechanical effects of vegetation on slope stability: A review. *Science of the Total Environment*, 926, 171691. <https://doi.org/10.1016/j.scitotenv.2024.171691>
25. Lee, C. P. (2001). Scarcity of fossils in the Kenny Hill Formation and its implications. *Gondwana Research*, 4(4), 675–677. [https://doi.org/10.1016/S1342-937X\(05\)70473-7](https://doi.org/10.1016/S1342-937X(05)70473-7)
26. McKenzie, N., Jacquier, D., Isbell, R., Brown, K. (2004). *Australian soils and landscapes: An illustrated compendium*. CSIRO Publishing.
27. Mir, S. I., Gasim, M. B., Rahim, S. A., Toriman, M. E. (2010). Soil loss assessment in the Tasik Chini catchment, Pahang, Malaysia. *Bulletin of the Geological Society of Malaysia*, 56, 1–7. <https://doi.org/10.7186/bgsm56201001>
28. Mohamed, Z., Rafek, A. G., Komoo, I. (2007). Characterisation and classification of the physical

- deterioration of tropically weathered Kenny Hill rock for civil works. *Electronic Journal of Geotechnical Engineering*, 12, Bundle A, Article 16.
29. Mohamed, W. N. A. W., Osman, N., Abdullah, R. (2023). A review of bioengineering techniques for slope stability in Malaysia. *International Journal of Environmental Science and Technology*, 20(3), 3467–3482. <https://doi.org/10.1007/s13762-022-04235-3>
 30. Normaniza, O., Aimee, H., Ismail, Y., Tan, G. Y. A., Rozainah, M. Z. (2018). Promoter effect of microbes in slope eco-engineering: Effects on plant growth, soil quality and erosion rate at different vegetation densities. *Applied Ecology and Environmental Research*, 16(3), 2219–2232. https://doi.org/10.15666/aeer/1603_22192232
 31. Olabode, O. P., Lim, H. S., Ramli, M. H. (2022). Geophysical and geotechnical evaluation of landslide slip surface in a residual soil for monitoring of slope instability. *Earth and Space Science*, 9(12), e2022EA002248. <https://doi.org/10.1029/2022EA002248>
 32. Osman, K. T. (2012). *Soils: Principles, properties and management*. Springer. <https://doi.org/10.1007/978-94-007-5663-2>
 33. Ozcep, F., Yildirim, E., Tezel, O., Asci, M., Karabulut, S. (2010). Correlation between electrical resistivity and soil-water content based artificial intelligent techniques. *International Journal of Physical Sciences*, 5(1), 47–56.
 34. Paramanathan, S., Muhamad, N., Pereira, J. J. (2021). Soil related factors controlling erosion and landslides in Malaysia. *Bulletin of the Geological Society of Malaysia*, 72, 165–175. <https://doi.org/10.7186/bgsm72202113>
 35. Qasim, S., Harahap, I. S. H., Osman, S. B. S. (2013). Causal factors of Malaysian landslides: A narrative study. *Research Journal of Applied Sciences, Engineering and Technology*, 5(7), 2303–2308. <https://doi.org/10.19026/rjaset.5.4656>
 36. Rahardjo, H., Ong, T. H., Rezaury, R. B., Leong, E. C. (2007). Factors controlling instability of homogeneous soil slopes under rainfall. *Journal of Geotechnical and Geoenvironmental Engineering*, 133(12), 1532–1543. [https://doi.org/10.1061/\(ASCE\)1090-0241\(2007\)133:12\(1532\)](https://doi.org/10.1061/(ASCE)1090-0241(2007)133:12(1532))
 37. Rahman, H. A., Mapjabil, J. (2017). Landslides disaster in Malaysia: An overview. *Health and the Environment Journal*, 8(1), 58–71.
 38. Rahman, M. A., Lee, S.-H., Ji, H. C., Kabir, A. H., Jones, C. S., Lee, K.-W. (2018). Importance of mineral nutrition for mitigating aluminum toxicity in plants on acidic soils: Current status and opportunities. *International Journal of Molecular Sciences*, 19(10), 3073. <https://doi.org/10.3390/ijms19103073>
 39. Raza, I., Ullah, H., Ehsan, M. I., et al. (2025). An integrated geophysical and geotechnical solutions for assessing slope instability challenges in open-pit mining: safeguarding mining operations. *Bulletin of Engineering Geology and the Environment*, 84, 83. <https://doi.org/10.1007/s10064-025-04124-2>
 40. Reynolds, J. M. (2011). *An introduction to applied and environmental geophysics (2nd ed.)*. Wiley-Blackwell.
 41. Samouëlian, A., Cousin, I., Tabbagh, A., Bruand, A., Richard, G. (2005). Electrical resistivity survey in soil science: A review. *Soil and Tillage Research*, 83(2), 173–193. <https://doi.org/10.1016/j.still.2004.10.004>
 42. Siddiqui, F. I., Osman, S. B. A. S. (2012). Integrating geo-electrical and geotechnical data for soil characterization. *International Journal of Applied Physics and Mathematics*, 2(2), 104–106. <https://doi.org/10.7763/IJAPM.2012.V2.69>
 43. Sidle, R. C., Ochiai, H. (2006). *Landslides: Processes, prediction, and land use*. American Geophysical Union. <https://doi.org/10.1029/WM018>
 44. Soil Survey Staff. (2017). *Soil survey manual* (C. Ditzler, K. Scheffe, H. C. Monger, Eds.). U.S. Department of Agriculture, Natural Resources Conservation Service. <https://www.nrcs.usda.gov/resources/guides-and-instructions/soil-survey-manual>
 45. Stokes, A., Douglas, G. B., Fourcaud, T., Giadrosich, F., Gillies, C., Hubble, T., Kim, J. H., Loades, K. W., Mao, Z., McIvor, I. R., Mickovski, S. B. (2014). Ecological mitigation of hillslope instability: ten key issues facing researchers and practitioners. *Plant and Soil*, 377(1), 1–23. <https://doi.org/10.1007/s11104-014-2044-6>
 46. Tarmidzi, S. N. A., Rahman, Z. A., Masri, I. N., Osman, N., Idris, W. M. R., Aznan, M. E., Jasni, Z., Ruzi, A. R., Lihan, T., Ettbeb, A. E. (2026). A decade of soil bioengineering for erosion control in Malaysia: Progress, challenges, and future directions. *International Journal of Environmental Science and Technology*, 23(4), Article 319. <https://doi.org/10.1007/s13762-026-07080-w>
 47. Wicharuck, S., Khongdee, N., Mawan, N., Stahr, K. (2023). Soil erosion assessment under different land use types using modified Gerlach trough in North-Western Thailand Highland. *Soil Science Annual*, 74(1), Article 163079. <https://doi.org/10.37501/soilsa/163079>
 48. Yamasaki, S.-I., Yamagishi, H., Tsuchiya, N. (2023). Major element analysis of geological samples with wavelength dispersive X-ray fluorescence (WDXRF) spectrometry using glass disks and pressed powder pellets. *Sustainable Environment*, 9(1), Article 2251805. <https://doi.org/10.1080/27658511.2023.2251805>
 49. Yin, E. H. (2011). *Geology and mineral resources of the Kuala Lumpur–Kelang area* (Map Report 22). Minerals and Geoscience Department Malaysia.