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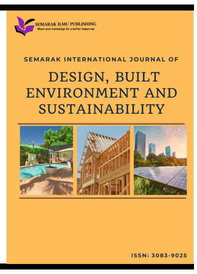

Slope Factor of Safety Assessment using Spectroradiometer Data and Unmanned Aerial Vehicle Imagery

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ABSTRACT

Slope instability is a critical geotechnical challenge in tropical regions, where intense rainfall and rapid land development frequently trigger landslides. In Malaysia, annual monsoon rainfall reduces soil shear strength, while deforestation and slope modifications further increase the risk of slope failure. However, conventional methods are often time-consuming and lack the capacity for real-time monitoring. By integrating remote sensing techniques, this study enhances the efficiency and spatial coverage of slope stability assessments while reducing the reliance on labour-intensive field investigations. This study aims to establish the relationship of the factor of safety (FOS) of soil slope with vegetation spectral analysis using vegetation indices (VI) and unmanned aerial vehicle (UAV) based on digital mapping. Over a six-month period (October 2023–March 2024) at Dusun UTM, the factor of safety (FOS) was evaluated alongside vegetation indices (VI) derived from spectroradiometer measurements. VI values ranged from 0.1 to 0.6, where higher values reflected denser, healthier vegetation. These higher VI values were consistently associated with FOS values between 3.0 and 4.0, representing stable slope conditions. Although indices such as NDVI and SAVI are widely used in vegetation monitoring, their direct application to slope stability assessment remains limited. This integrated monitoring approach demonstrates the potential VI values as proxies for slope stability assessment, offering a scalable method for early detection of slope weakening in tropical environments.

1. Introduction

In tropical areas, where heavy monsoon rains and urban growth lead to landslides more likely, slope instability is a major issue for engineers. Malaysia receives an average of 2,400 mm of rain each year, which makes it more likely to have landslides because rain is one of the primary triggers [1]. Rahardjo *et al.,* [2] mentioned that slope instability is one of the major issues that engineers need to face in tropical areas, in which heavy monsoon rains and urban growth cause landslides. Population growth and infrastructure demands, such as highway construction and road widening, lead to mass land clearing, with development expanding into hilly areas as flat terrain becomes increasingly

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limited [3]. Every year, these natural disasters cause deaths and damage to thousands of people and are one of the most dangerous and widespread risks in the world. Vegetation proved very important for keeping the slope stable and controlling erosion triggered by both mechanical and water-related factors are taken from previous study [4-6]. Plant roots help improve the soil structure, increase its non-capillary porosity, reduce the soil bulk, and enhance the soil's infiltration performance, allowing rainwater to soak into the ground rather than rush down the slope surface [7].

A clear example happened in December 2022 at Father's Organic Farm in Batang Kali, Selangor. Heavy rains that would not stop, weakened the steep hillside above a campsite, causing an enormous landslide that killed 31 people, including 13 children. The disaster buried the camping area under massive amounts of dirt and debris. As for the landslide tragedy, Hasan [8] stated that somebody had already cleared the forest cover for an organic farming project, and a camping area was added. As a result, the exposed slopes in the area were not replanted with native trees to control erosion. Furthermore, excessive rainfall flows over the surface during rainy seasons and infiltrates the soil's slope. Lin and Zhong [9] stated that these factors significantly reduce soil shear strength, compromising slope stability and decreasing the factor of safety (FOS).

Lin *et al.,* [10] stated that removing trees plays a crucial role in slope instability due to the loss of root reinforcement, which is vital in maintaining soil cohesion. Previous studies have shown that tree roots enhance water infiltration and increase soil stability against erosion, which reduces the probability of shallow landslides throughout heavy rainfall events [11-13]. Dorairaj and Osman [14] stated that vegetation developed as a mechanism for restoring slope stability while also improving their physical condition throughout the succession process. Previous studies have focused on the impact of specific plant species on slope stability [15-17]. They also learn that tree roots can help and support the soil against slope failures because of how they affect the soil's structure and moisture content through processes like evapotranspiration.

Previous research has proven and studied multiple solutions to the found problems while assessing root reinforcement within a wider framework [18]. In this case, remote assessment is performed using advanced remote sensing technologies, which include an unmanned aerial vehicle (UAV) and a spectroradiometer. According to Rasib *et al*., [19], the use of remote sensing technologies has greatly improved the techniques used to collect data in geodesy. The UAV was the newest technology, which had become popular for mapping in remote sensing in the field of geotechnical engineering are taken from previous study [20,21]. It is an application that uses of UAV for close-range remote sensing. The UAV offers better both temporal and spatial resolution thanks to its ease of use, affordability, minimal time spent and minimized risk for researchers [22]. Also, using a UAV for this research proves especially suitable for surveying extensive areas while accurately showing the entire slope study region [23].

The additional data for this study involves field observations performed with a spectroradiometer. The purpose of the spectroradiometer observation was to collect more accurate data in a small area, focused on one tree [24]. The use of spectroradiometer data in slope stability research has grown, as Zocchi *et al*., [25] stated, spectral indices can help us understand surface processes that lead to slope failure. The Normalized Difference Vegetation Index (NDVI) and the Soil Adjusted Vegetation Index (SAVI) are two examples of vegetation indices that have been used to keep track of changes in vegetative cover [26]. Mehmood *et al.,* [27] found that a decrease in NDVI over time was often associated with heightened soil erosion and instability, especially in areas affected by seasonal rainfall.

Current slope monitoring practices in Malaysia are largely reactive, focusing on post-failure assessments rather than proactive prevention. Conventional methods are time-consuming and lack the capability for real-time monitoring. In contrast, emerging remote sensing technologies such as spectroradiometers offer new opportunities for early detection of changes in vegetation health and soil moisture for both critical indicators of slope stability. However, the integration of these advanced sensing tools with traditional geotechnical techniques remains limited in the Malaysian context. This study addresses this gap by introducing a combined monitoring framework that integrates spectroradiometer data with established geotechnical methods to enhance early warning capabilities and promote more effective, sustainable slope management.

2. Methodology

A mixed-method approach combines geotechnical field data with spectral vegetation analysis, which is used. Data for this study were collected monthly over a six-month period (October 2023 to March 2024) at residual soil slope in Dusun UTM, with six (6) samplings dates and twelve (12) measurement points for each condition (with and without tree). Comprehensive field monitoring was conducted using tensiometers, gypsum blocks, and rainfall gauges to measure soil matric suction and rainfall, while vegetation indices (VI) were obtained from spectroradiometer (RS-3500) readings. Previous study shows that slope stability was analysed using SLOPE/W software to calculate the factor of safety (FOS) under various conditions, both with and without tree cover [28,29]. In addition, an unmanned aerial vehicle (UAV) surveys were carried out to generate georeferenced orthophotos and digital surface models (DSM), providing detailed spatial information on terrain elevation and slope conditions to support the stability analysis are taken from previous study [30-32].

2.1 Study Area

The study was conducted at Dusun UTM, located on the middle of the slope at coordinates (N 1.5642°, E 103.6253°) as shown in Figure 1. Previous study have shown the site is characterized by tropical climatic conditions with frequent rainfall and sandy silt soil [33,34]. A single *Bridelia Stipularis* tree located at the midpoint of the slope was selected due to its prominent position and potential influence on slope hydrology and mechanics. The slope was monitored for changes in soil water content and stability.

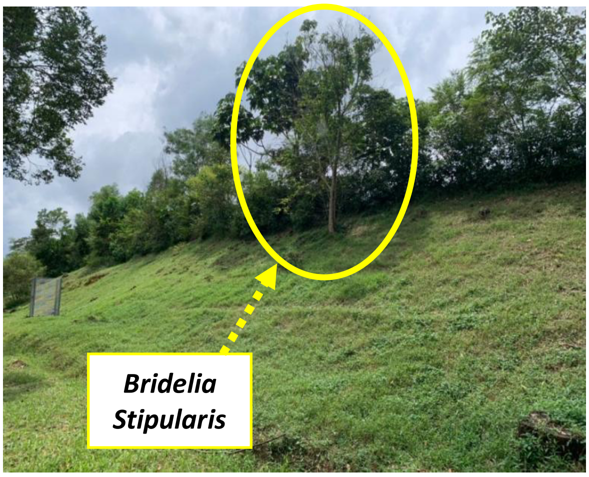

Fig. 1. *Bridelia Stipularis* tree located at the middle of slope Dusun UTM

2.2 Geotechnical Field Monitoring Works

Tensiometers and gypsum blocks were installed at different depths of 0.5 m, 1.0 m, 1.5 m, and 2.0 m along the critical slip surface to monitor soil matric suction. Rain gauges were also used to quantify precipitation, enabling the correlation between rainfall events and changes in suction. This monitoring is to observe how transpiration-induced suction from the tree influences slope stability [35]. Figure 2 displays the tensiometers and gypsum blocks installed at the slope area.

Fig. 2. The installation of tensiometers and gypsum blocks at slope area

2.3 Unmanned Aerial Vehicle (UAV)

Several essential pieces of equipment, as shown in Figure 3, are required for this study, comprising a full set of commercial unmanned aerial vehicles (UAV). This includes the DJI Inspire 1 UAV equipped with a Micasense camera, remote controller and MicaSense calibration panel case. According to Vishweshwaran and Sujatha [36],the UAV derived digital surface models (DSM) and orthophotos were validated using ground control points (GCPs) collected through Real Time Kinematic Global Positioning System (RTK GPS) surveys. A series of well distributed GCPs were established across the study area to ensure accurate georeferencing and alignment of the UAV imagery. The coordinates of these points were measured with a positional accuracy of less than 5 cm, serving as reference markers for correcting spatial distortions during the photogrammetric processing stage. The accuracy of the final DSM and orthophotos was further evaluated by comparing the UAV derived coordinates with the RTK GPS GCP data, confirming high spatial reliability suitable for terrain analysis and slope stability assessment.

Fig. 3. DJI Inpire 1 UAV

2.4 Spectroradiometer

Figure 4 shows the Spectral Evolution (RS-3500) and its accessories, which include a pistol grip and white reflectance. It can be used to detect wavelengths from 350nm to 2500nm. The reading of the spectroradiometer was recorded by a data logger using the Getac model.

Spectroradiometer readings were calibrated using a white reference panel before each measurement to minimize reflectance error and ensure data consistency are taken from previous study [37,38]. Prior to data acquisition, the instrument's sensor was first dark-calibrated to account for internal electronic noise, followed by calibration with a standard white reference panel to establish a baseline for 100 percent reflectance. This procedure was repeated periodically throughout the field campaign to compensate for changes in ambient light conditions, such as variations in solar angle or cloud cover. By performing both dark and white reference calibration, the accuracy and reliability of the spectral reflectance measurements were maintained, enabling precise calculation of vegetation indices (VI) used in the analysis.

Fig. 4. Spectral Evolution (RS-3500) and its accessories

3. Result and Discussion

This sub-chapter presents the results of the factor of safety (FOS) and vegetation indices (VI) that were calculated from spectroradiometer measurements. These measurements have become popular in slope stability studies. From this spectral data, indices such as the Normalized Difference Vegetation Index (NDVI) and the Soil Adjusted Vegetation Index (SAVI) were calculated. These indices serve as indirect indicators of plant vigor and transpiration possibility, in which both are closely related to a tree's capability to induce suction in the soil. In addition, UAV surveys provided orthophotos and digital surface models (DSM), which offered spatial data on terrain elevation and slope conditions to complete the spectral and geotechnical analysis. Finally, the integration of these datasets produced slope classification based on the factor of safety (FOS) and vegetation indices (VI).

3.1 Analyses of Slope Stability

Figure 5 compares the factor of safety (FOS) between slopes with and without trees from October 2023 to March 2024. This provides us with the required information about the stability of slopes. According to the conventional geotechnical standards, the FOS value that is greater than 1.0 is generally considered stable, while values less than 1.0 indicate potential instability and a high risk of failure [39].

During the monitoring period, the slope with a tree consistently showed greater stability than the slope without a tree, as shown by consistently higher FOS values. The tree (*Bridelia Stipularis*) had a significant buffering effect against FOS reductions during rain events, and both scenarios stayed the same. The data showed that both slopes' FOS values changed during the periods of moderate to heavy rainfall (up to 160 mm). These higher values were associated with FOS values between 3.0 and 4.0, indicating more stable slope conditions.

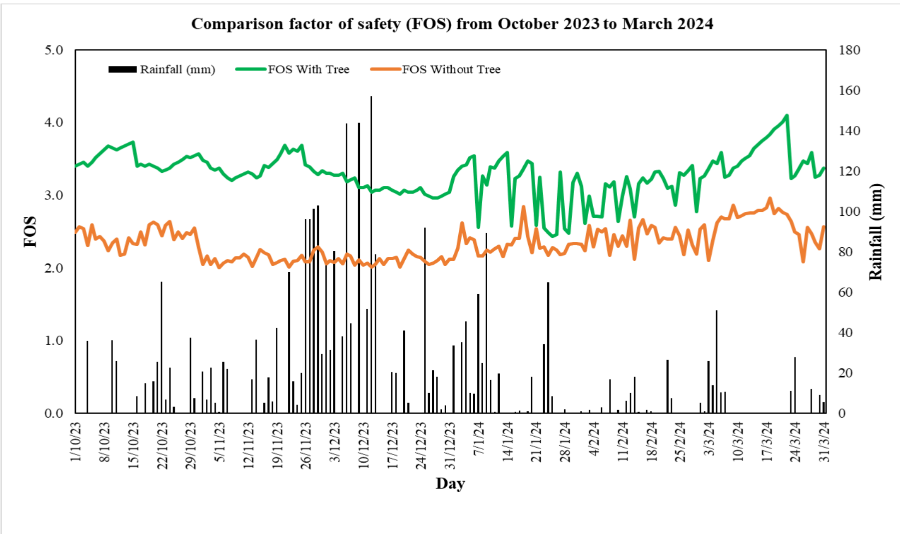

Fig. 5. Comparison of factor of safety (FOS) for slopes with and without a tree at the middle of the slope from October 2023 to March 2024

3.2 UAV Digital Mapping

The captured high-resolution imagery underwent comprehensive photogrammetric processing, resulting in the generation of detailed spatial products for the Dusun UTM slope. These products included a georeferenced digital orthophoto, which provided a precise planimetric representation of the study area, as shown in Figure 6. A digital surface model (DSM) that accurately depicts the terrain elevation and surface features is shown in Figure 7.

Fig. 6. Digital orthophoto from UAV digital mapping at Dusun UTM

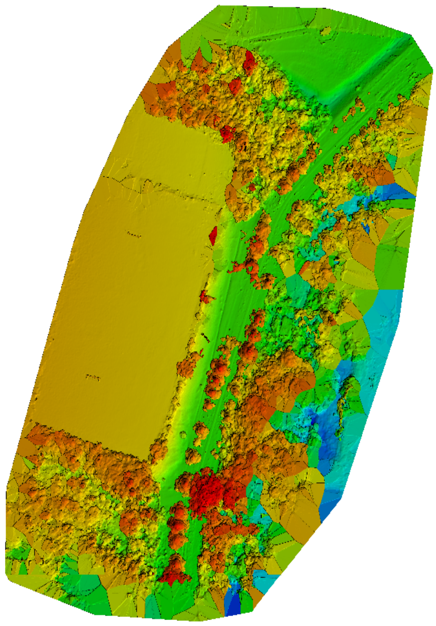

Fig. 7. Digital surface model (DSM) from UAV digital mapping at Dusun UTM

The three-dimensional (3D) visualization of Dusun UTM was generated using Pix4D Mapper. This 3D representation was derived from the processed UAV data, enabling detailed visualization of the study area's complex topography, including variations in terrain. Table 1 presents the measurement of the slope of Dusun UTM, including the feature type and its respective measurements.

Table 1
Measurement of slope Dusun UTM

Feature Types	Measurements
Terrain 3D area	2658.07 m^2
Cut volume	46.18 m^3
Fill volume	7.16 m^3
Total volume	53.35 m^3

From Table 1, the topographical analysis of the study area revealed several key terrain measurements. The 3D surface area of the terrain encompassed 2,658.07 m^2, indicating the total ground coverage when accounting for slope variations and surface irregularities. The volumetric analysis revealed that the cut volume requirements were 46.18 m^3, while the fill volume requirements were substantially lower at 7.16 m^3. The combined total volume of earthwork operations amounted to 53.35 m^3. These measurements were essential for understanding the site's topographical characteristics and potential earthwork requirements for slope modification or stabilization efforts.

3.3 Derivation of Vegetation Indices from Spectroradiometer Data

The classification of plant health using vegetation indices (VI) such as the Normalized Difference Vegetation Index (NDVI) and Soil-Adjusted Vegetation Index (SAVI) indicates distinct thresholds corresponding to different plant health conditions [40]. Healthy plants exhibit NDVI values ranging from 0.67 to 1.00 and SAVI values between 0.55 and 1.00, reflecting high photosynthetic activity and dense vegetation cover. Moderately healthy plants show NDVI values between 0.15 and 0.66 and SAVI values within 0.13 to 0.54, suggesting moderate vegetation vigor. In contrast, plants under stress are characterized by NDVI values below 0.14 and SAVI values below 0.12, indicating poor vegetation health and reduced chlorophyll content.

Table 2 presents the values of vegetation indices and rainfall data collected from October 2023 to December 2023 (wet season) and January 2024 to March 2024 (dry season). The table included three key parameters: the Normalized Difference Vegetation Index (NDVI), the Soil Adjusted Vegetation Index (SAVI) for areas with and without trees and the daily rainfall amounts.

Table 2
Value between vegetation indices and rainfall from October 2023 until March 2024

Month	Rainfall (mm/day)	NDV1	SAV1 (with tree)	SAV1 (without tree)
October 2023	15	0.446	0.207	0.264
November 2023	42.2	0.436	0.386	0.264
December 2023	41	0.473	0.170	0.134
January 2024	0.2	0.392	0.369	0.315
February 2024	1.2	0.467	0.316	0.265
March 2024	0	0.441	0.376	0.283

The NDVI values ranged from 0.392 to 0.473 over the six months. The highest value (0.473) was in December 2023, indicating peak vegetation health or density and January 2024 had the lowest value (0.392), reflecting a decrease in vegetation, possibly because of the dry season. SAVI values were provided for two distinct scenarios: soil with a tree and soil without a tree. For soil with a tree, SAVI values fluctuated between 0.170 and 0.386. The highest value was observed in November 2023 (0.386), while the lowest was in December 2023 (0.170). For soil without a tree, SAVI values ranged from 0.134 to 0.406, with the highest value also occurring in November 2023 (0.406) and the lowest in December 2023 (0.134). Rainfall data showed differences throughout the months, with November and December 2023 being the driest, recording 42.2 mm/day and 41 mm/day of rain, respectively. In contrast, January and February 2024 saw extremely dry weather, with rainfall amounts of 0 mm/day and 0.2 mm/day, respectively.

The Normalized Difference Vegetation Index (NDVI) was a widely used indicator of vegetation density and vigor. High NDVI values typically indicated healthy, dense vegetation, which contributed to slope stability through root reinforcement and increased evapotranspiration. Vegetation helped to intercept rainfall, reduce surface runoff, and enhance infiltration, thereby decreasing the likelihood of rapid pore water pressure buildup during precipitation events. A high NDVI value, especially if there is a lot of vegetation cover, was usually linked to a higher factor of safety (FOS), considering that vegetation made the slope surface stronger.

The Soil Adjusted Vegetation Index (SAVI) is similar to the NDVI, but it is specifically adjusted to reduce the effect of soil brightness in regions with light vegetation cover. SAVI was especially useful for detecting sparse or degraded vegetation. In slope studies, low SAVI values often pointed to exposed or degraded soil surfaces, which were more prone to erosion, infiltration-driven instabilities, and surface runoff concentration. Such conditions contributed to a reduction in the factor of safety (FOS). Contrarily, higher SAVI values, especially in areas with tree cover, indicated better soil protection and more stable slope conditions.

Rain was a major cause of the slope failure. Heavy rain, as well as prolonged precipitation, results in the soil becoming wetter, lowering its matrix suction and increasing pore water pressure, leading to a decrease in the factor of safety (FOS). However, rainfall also influenced the NDVI and SAVI values indirectly through its effect on vegetation health. When it rained a lot, plants tended to flourish better, which increased both the NDVI and SAVI values. This might assist in maintaining things stable in the long run. On the other hand, when it is dry, vegetation stress often which lowers the NDVI and SAVI value. This could make roots less stable and make erosion of the surface more likely.

High NDVI and SAVI values, which meant dense and healthy vegetation, were associated with improved slope stability. Vegetation contributed to increasing the FOS through root reinforcement, reduced surface runoff, and improved infiltration capacity. On the other hand, low NDVI and SAVI values showed that the plants were in sparse or stressed conditions, which often meant that the roots were less cohesive and the risk of erosion happening was higher. These made the FOS lower. In conclusion, the results showed that the NDVI and SAVI values in this range mostly fall between 0.1 and 0.6. This means that the plants are moderately healthy.

3.4 Relationship between Factor of Safety (FOS) and Vegetation Indices (VI)

There is a strong relationship between FOS and VI, as vegetation helps to ensure the stability of the slopes through its mechanical reinforcement and hydrological effects. Some well-growing plants may enhance erosion control, drainage and structural support for the soil, which can increase the factor of safety and give rise to the slope to become stable overall.

The relationship of the factor of safety (FOS) with vegetational indices (VI) is analyzed further in Figures 8. Figure 8 exhibited a proportional linear correlation between FOS with a tree and SAVI with a tree. As SAVI with the tree increased, FOS with tree also increased, indicating that higher vegetation cover with tree contributed to more excellent slope stability. The trendline was defined by the equation $y = 1.8157x + 2.8464$, meaning that this positive slope indicated a direct correlation between FOS with a tree and SAVI with tree. The R^2 value was 0.407, suggesting that 40.7% of the variability in FOS with tree could be explained by SAVI with a tree, indicating a moderate relationship between FOS with tree and SAVI with tree.

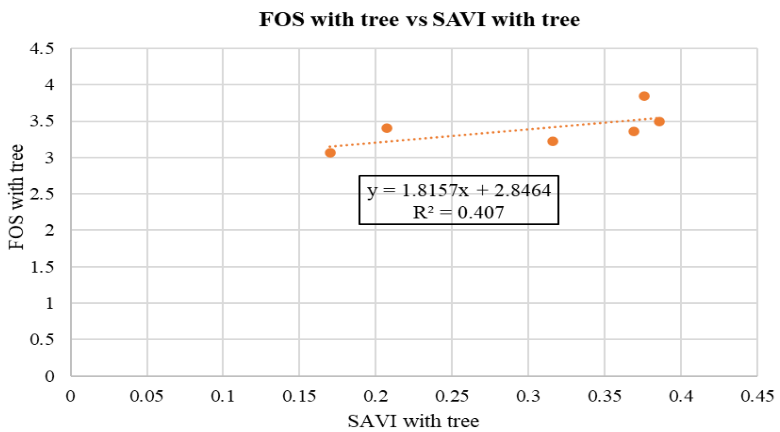

Fig. 8. The relationship between factor of safety (FOS) with tree and the Soil Adjusted Vegetation Index (SAVI) with tree

3.5 Slope Classification Based on Factor of Safety (FOS) and Vegetation Indices (VI)

In this section, six specific dates based on the spectroradiometer observations conducted in the study area are listed whereas 18th October 2023, 19th November 2023, 20th December 2023, 18th January 2024, 18th February 2024, and 18th March 2024. The collected data are the rainfall measurements, the factor of safety (FOS) values for both with and without a tree, Normalised

Difference Vegetation Index (NDVI) values, and the Soil Adjusted Vegetation Index (SAVI) values (with and without a tree).

The safety values and vegetation indices (NDVI and SAVI) for the six selected dates were applied to the map of Dusun UTM, which had been generated earlier using an unmanned aerial vehicle (UAV). These safety maps were presented under two conditions: with and without a tree. All the maps are shown in Figures 9 through Figure 14.

During the wet season, the factor of safety (FOS) for slopes with trees remained consistently within the range of 3.01–3.50 (green) over three consecutive months. Despite increased rainfall and a higher risk of slope instability, these tree-covered slopes maintained stable FOS values, indicating that vegetation effectively buffered the impact of rainfall. This stabilization is a result of transpiration-induced suction, which decreases the pore water pressure and canopy interception that prevents direct rain from reaching the soil surface and root reinforcement, which strengthens soil cohesion and stops mass movement. Otherwise, slopes without trees consistently showed lower FOS values, which ranged between 2.01 and 2.50 (yellow), indicating marginal stability. These conditions showed that without vegetation, slopes are more directly affected by hydrological stress, which leads to an increase in moisture levels and a decreased of the soil shear strength, thus raising the risk of failure, especially during intense rainfall.

In the dry season, the FOS for slopes with trees remained stable at 3.01–3.50 (green) in January and February 2024, consistent with the wet season values, indicating that the stabilizing benefits of tree-induced suction and root reinforcement persist even with minimal water input. The FOS showed an increase again by March 2024, reaching a range between 3.51–4.00 (purple), which is the highest recorded range. This showed that soil moisture levels dropped even more because of the continued transpiration and evaporation by the vegetation, and it also shows that the slope condition is even more stable, with a very low risk of failure. This improvement also highlights the cumulative effect of vegetation over time in enhancing soil structure and strength. In contrast, slopes without trees showed a slight improvement compared to the wet season, with FOS values rising to 2.51–3.00 (orange), likely due to the natural reduction in pore water pressure under drier conditions. However, these slopes remained significantly less stable than those with vegetation, emphasizing that natural drying alone cannot match the effectiveness of tree cover in reinforcing and stabilizing slopes.

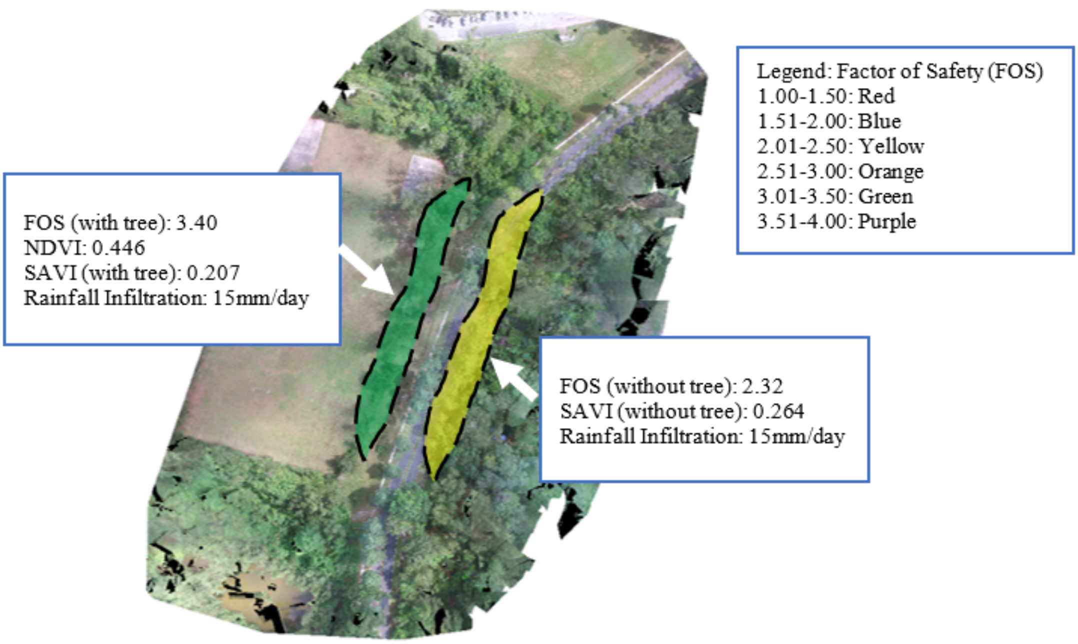

Fig. 9. Factor of safety (FOS), vegetation indices (VI) and rainfall data on 18th October 2023

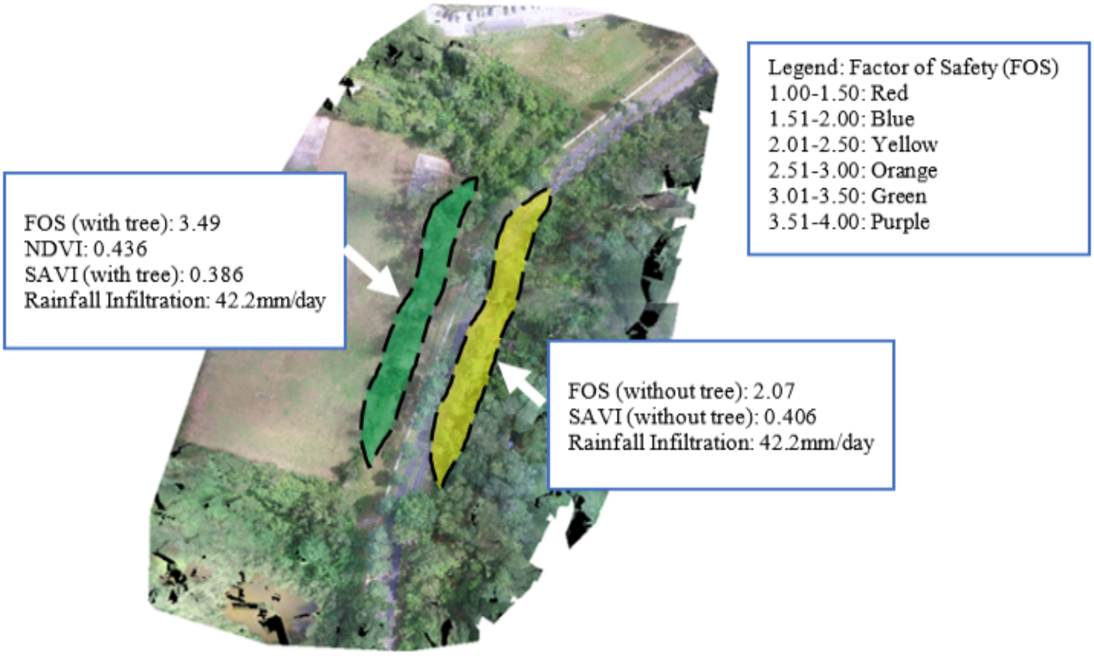

Fig. 10. Factor of safety (FOS), vegetation indices (VI) and rainfall data on 19th November 2023

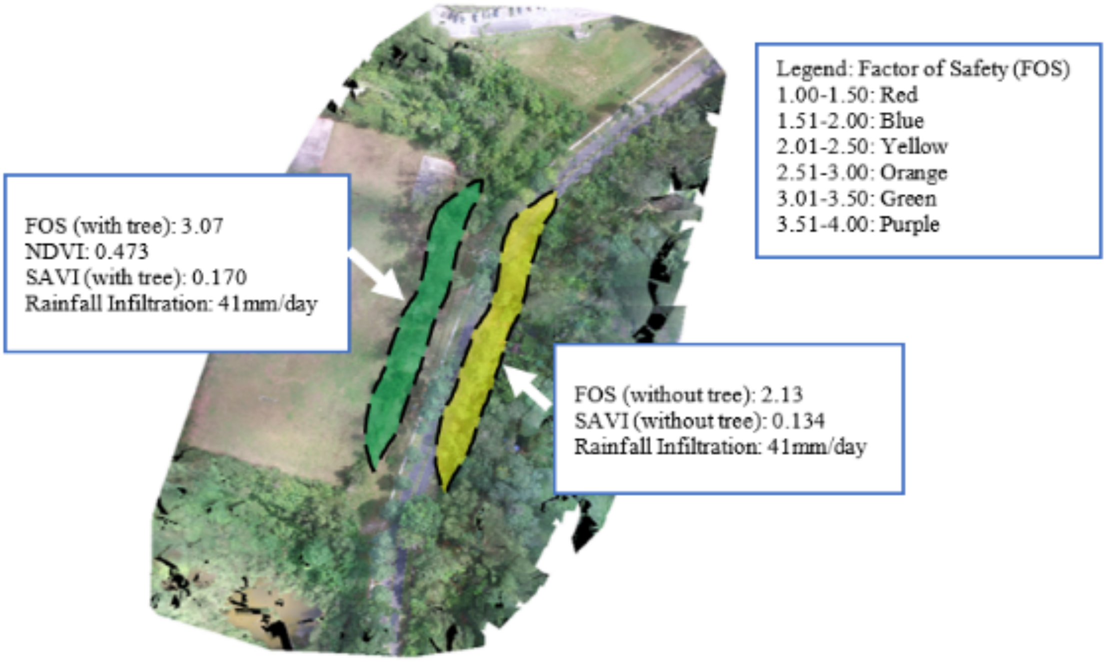

Fig. 11. Factor of safety (FOS), vegetation indices (VI) and rainfall data on 20th December 2023

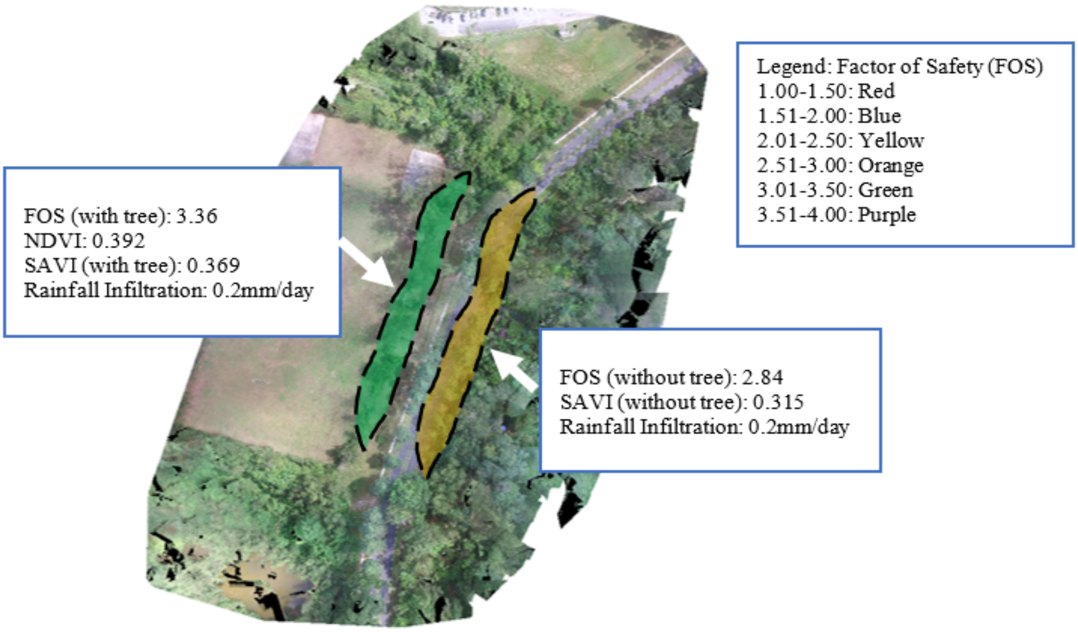

Fig. 12. Factor of safety (FOS), vegetation indices (VI) and rainfall data on 18th January 2024

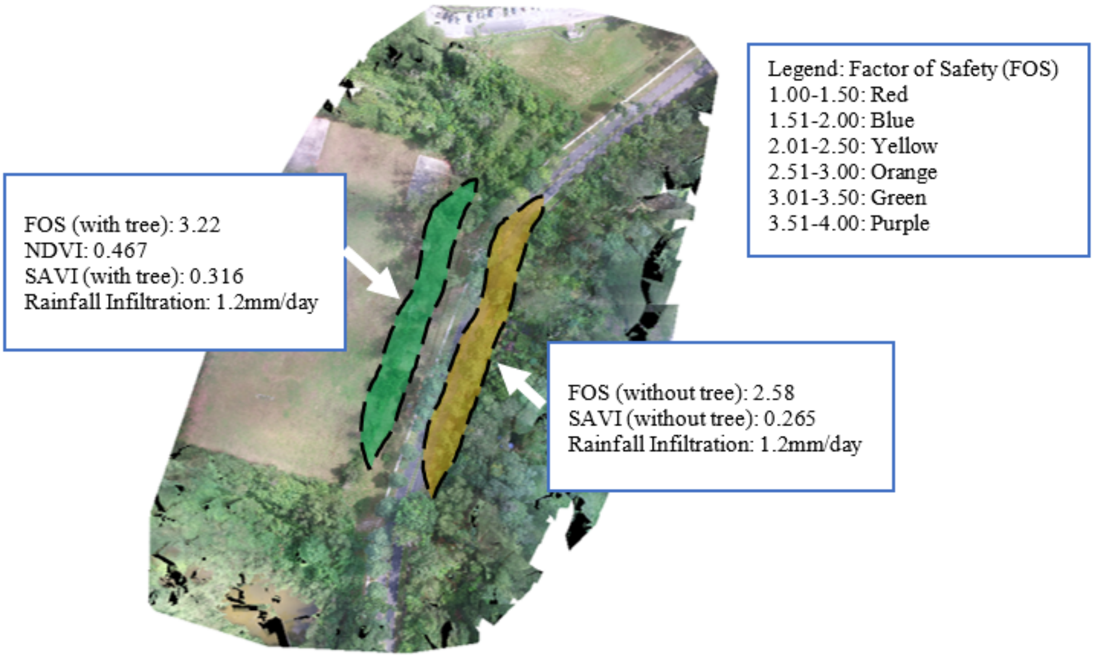

Fig. 13. Factor of safety (FOS), vegetation indices (VI) and rainfall data on 18th February 2024

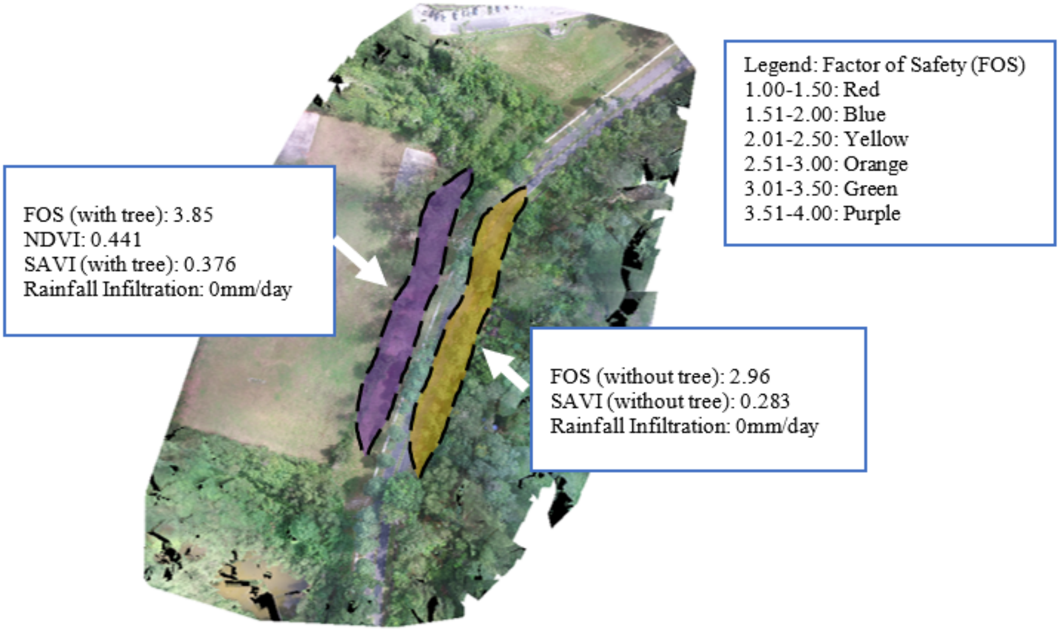

Fig. 14. Factor of safety (FOS), vegetation indices (VI) and rainfall data on 18th March 2024

4. Conclusion

The findings demonstrate that integrating spectral and geotechnical datasets provides a mechanistic understanding of slope behaviour, where vegetation-induced suction acts as a controlling factor in maintaining stability. UAV imagery enables detailed digital mapping of terrain morphology, while spectroradiometer data quantify vegetation health, which influences hydrological behaviour. Geotechnical monitoring complements these datasets by verifying physical stability through suction and factor of safety (FOS) measurements. The integration of these approaches establishes a multidimensional understanding of slope stability.

The results reveal that moderate to high vegetation index (VI) values correspond to stable slope conditions (FOS > 3), confirming the protective role of healthy vegetation. Higher VI values are associated with increased transpiration-induced suction and enhanced root reinforcement, both of which reduce pore water pressure and improve soil cohesion, thereby increasing the FOS.

However, these findings should be interpreted within the constraints of the six-month monitoring period and potential atmospheric interference during spectral measurements. Furthermore, the model's applicability to steeper slopes or diverse vegetation types requires additional validation.

Overall, the results provide a strong scientific basis for integrating vegetation health monitoring into slope management frameworks, enabling local authorities and developers to adopt proactive measures for land-use planning, erosion control, and sustainable infrastructure development. Future research should incorporate multi-year monitoring to capture inter-seasonal variability, extend the analysis to various vegetation types with different rooting systems, and explore the use of machine learning models to predict slope failure risk based on vegetation dynamics.

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