



Effect of *Alstonia Angustiloba* tree moisture absorption on the stabilization of unsaturated residual soil slope

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Abstract

In this study, the investigation on the influence of *Alstonia Angustiloba* tree moisture absorption at various depths and separation on the development of persuaded moisture absorption in soil were performed. The slope stabilization analysis were conducted considering two conditions (dry and wet conditions) at two different slope (saturated and unsaturated slope). Besides, the tree moisture absorption data generated during the course of 8 months of on-site monitoring are recorded and applied to assess the safety factor of the slope. Slope stabilization analysis is then performed and represented in two-dimensional and three-dimensional contour model to investigate the effect of plant transpiration on the slope stabilization. According to the findings, at the slope crest with the existence of *Alstonia Angustiloba* tree, the tree moisture absorption recorded a maximum value, at a distance and depth of 1.1 and 0.25 m. Moreover, the findings also proved that larger tree moisture absorption enhanced the slope's safety factor by up to 53% (from 2.17 to 4.57). The tree moisture absorption can provide an environmentally benign technique that can be used globally to avert slope disaster.

Keywords Factor of safety · Rainfall infiltration · Shear strength · Slope stability · Tree-induced suction

Introduction

Residual soil is the most widespread in tropical areas where frequent precipitation and moderate temperatures may encourage erosion (Zolkepli et al. 2021a; Zolkepli et al. 2021b). Microstructure and mineralogical composition are the important characteristics that may contribute to the specific qualities of residuals soil (Schiavon et al. 2019; Hasan et al. 2021a, b, c, d; Zaini and Hasan 2023a, 2023). Various disasters such as landslide may be attributed to the weakness in various engineering characteristics of this soil (Oberhollenzer et al. 2018), especially the carrying capacity and strength of the soil (Zhang et al., 2022; Zaini and Hasan 2023a; 2023). Landslip may be accomplished by a single or combination of motions such as running, sliding, and collapsing (Zaini et al. 2020a, 2022a), and it has piqued

the attention of civil engineering researchers owing to the significant deflation (Goh et al. 2020; Zaini et al. 2020b).

Slope disintegrate on various types of slopes is significant because it threatened lives, leading to deflation, and degrades the climate (Ishak & Zaini 2018). Territorial communities and visitors are always exposed to the natural calamities such as overflowing, torrents, and wildfire (Pradhan & Siddique 2020). For the last 70 years, the issue of slope stabilization has been a cornerstone of research in the geological engineering profession and academia. Numerous methodologies proposed in accordance with current computational approaches have been rectified in order to achieve maturity in the engineering community (Hasan et al. 2021b; Zolkepli et al. 2021a; Bouzid 2022). However, there is no commonly accepted clarification for the safety factor. The safety factor is widely computerized for most slope stability problems based on the assumption of highest bearing load capability. Nonetheless, it is easier for slope stability calculations if the safety factor is linked to the usual strength properties of the soil (Awang et al. 2021).

Slope stabilization issues have piqued the interest of scientists all over the world, and as a result, several methodologies and application for evaluating the slope stabilization have been created (Chen et al. 2013; Zaini et al. 2019). Slope stabilization

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is the capacity of tilted slopes to oppose shifting and has a substantial implications for the infrastructure preservation such as roadways, levees, and railways (Basahel & Mitri 2017; Zolkepli et al. 2018; Ishak et al. 2021a). A slope calamity can be influenced by certain factors, either cooperating or isolated, measuring water seepage (Zolkepli et al. 2019; Bastola et al. 2020; Zaini et al. 2022b), chemical weathering of soil, snow disintegrating (Ishak et al. 2018; Hasan et. al., 2021c), and physical weathering of soils, caused by seismic tremors (Ni et al. 2018; Ishak et al. 2021b). Slope evaluation via stabilization techniques is difficult since the slope catastrophe may be attributed to the different components, as well as the trouble of locating the best probable slip surface in daily scenarios (Liang et al. 2020; Wang et al. 2021). Therefore, several techniques to slope stabilization require the use of green foliage via the tree moisture absorption approach.

Green foliage is thought to aid slope stabilization via soil barricade and root moisture absorption (Zhu et al. 2018; Feng et. al., 2020). Plant roots absorb moisture during the uptake process by chemical alteration, which results in dehydrating of the soil surrounding (Rees et al. 2006; Rees et al. 2012) and subsequently activating soil suction (Nyambayo and Potts 2010; Ai et al. 2020). The effect of roots structure is well known over the globe, but tree water absorption has yet to be thoroughly investigated (Woodman et al. 2020; Kardani et. al., 2021). Tree moisture absorption is one of the crucial factors that determine the temporal-spatial distribution of moisture substances in shallow verdure soil (Zaini et al. 2023a, b; Zhu & Zhang 2015).

Comprehensive analytic review has recently been studied to assess intake lured by various verdure types triggered by transpiration and vaporization process. Furthermore, observable evidence of an arrangement of root region that enhances soil moisture absorption gains exceptional attentiveness. Therefore, the primary objective of this study was to evaluate the influence of tree-induced suctions on soil moisture absorption and moisture arrangements of a slope. The *Alstonia Angustiloba* tree's matric suction might improve slope stability, and matric suction would be controlled by transpiration processes in a low residual soil slope, which alter FOS under varied rainfall circumstances.

The results and discussion part reviews the paper's major findings, followed by the study's conclusion in the concluding section. The current study was conducted in the Geotechnical Engineering Laboratory, Universiti Malaysia Pahang in Malaysia from 2020 to 2022.

Materials and methods

On-site study characterization

The on-site study location is presented in Fig. 1. The residual soil cut slope with the extant of single mature tree is

located in Pahang, Malaysia, as indicated in the image. The examined slope is homogeneous with a dimensions of 15 m width and 3 m high, with a solitary mature tree (*Alstonia Angustiloba*) at the top of the hill reaching up to 11 m in height. Thirty tensiometers and 30 gypsum blocks were set in the research area to evaluate the suction of the tree.

Determination of physical properties of soil

The sieve analysis, consistency limits, and specific gravity were examined to determine the physical properties of residual soil. The particle size distribution and hydrometer analysis was determined using BS 1377: Part 2: 2022 and ASTM D 422. The hydrometer test was used to measure the grain size arrangement particularly for particles smaller than 63 μm . The semi-logarithmic graph was used to depict the percentage passing versus sieve data.

The plasticity of soil may be determined numerically using Atterberg limits. The test technique was used to test residual tropical soil since the particle size range was smaller than 63 μm . The consistency limit test was carried out using the cone penetrometer method, following BS 1377: Part 2: 2022. Plasticity index (BS 1377: Part 2: 2022) refers to the arithmetic difference between the plastic and liquid limits.

The small pycnometer test (BS 1377: Part 2: 2022) was carried out to determine the specific gravity of the soil. The soil samples were placed within a tiny pycnometer with half of the pycnometer previously filled with distilled water and accommodated inside a vacuum container for 1 day. The mass of the pycnometer was then determined. The laboratory work for the physical properties is depicted in Fig. 2a.

Determination of shear strength parameters of the soil

A 38 mm diameter \times 76 mm height of samples (3three samples) were produced with a basic soil splitter for the triaxial compression test (BS 1377: Part 4: 2022), as depicted in Fig. 2b. The soil specimens moisture content, dry density, and bulk density were calculated before the triaxial test was conducted. At 100, 150, and 200 kPa of confining pressures, the estimation of both saturated (c' , φ') and unsaturated (φ^b) shear strength values was performed. According to Zaini et al. (2020a), in Malaysia, the consolidated isotropic undrained test is appropriate for analysing the soil's shear strength characteristics since majority of the ground is consolidated and undrained.



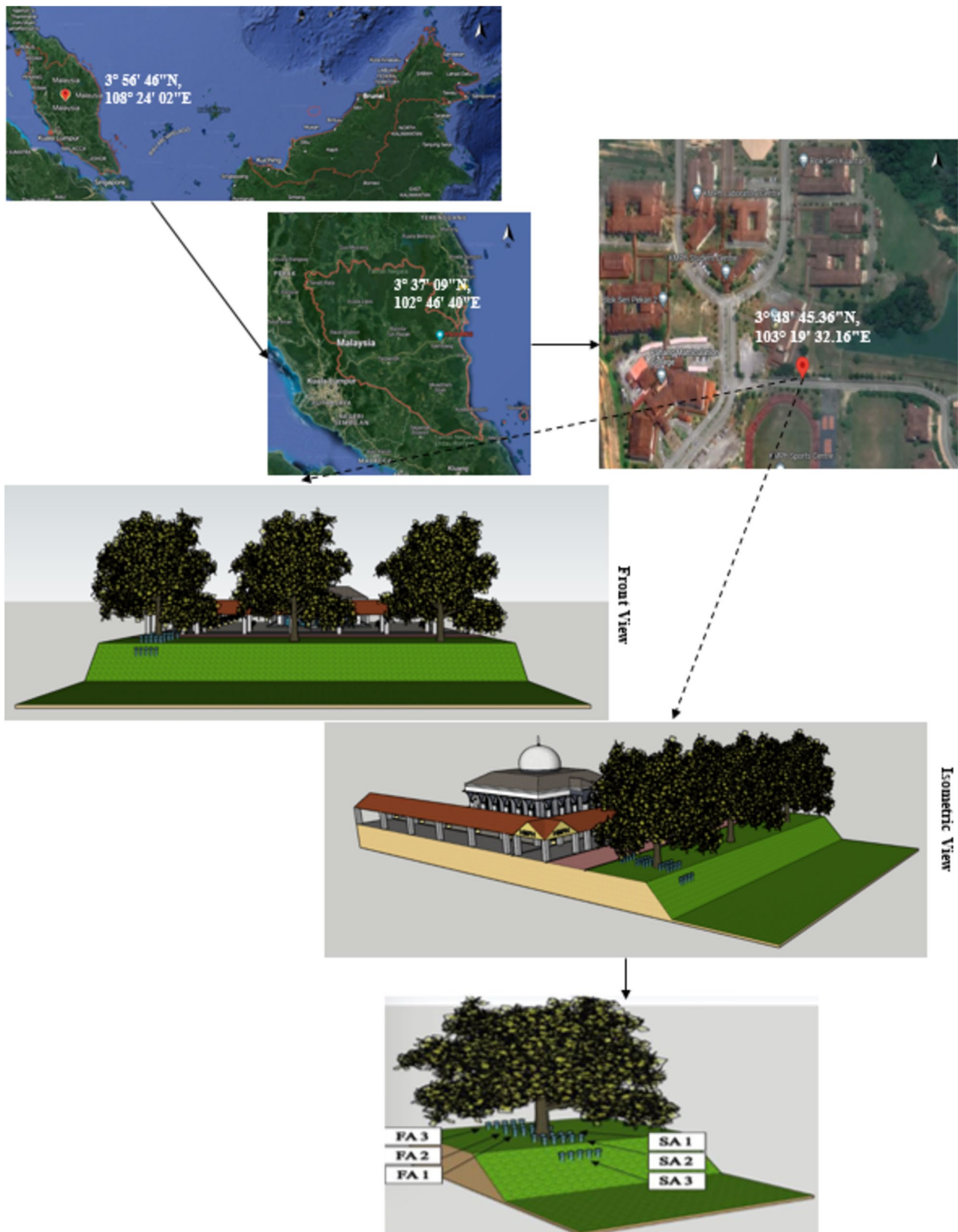


Fig. 1 Location of on-site monitoring of the tree moisture absorption

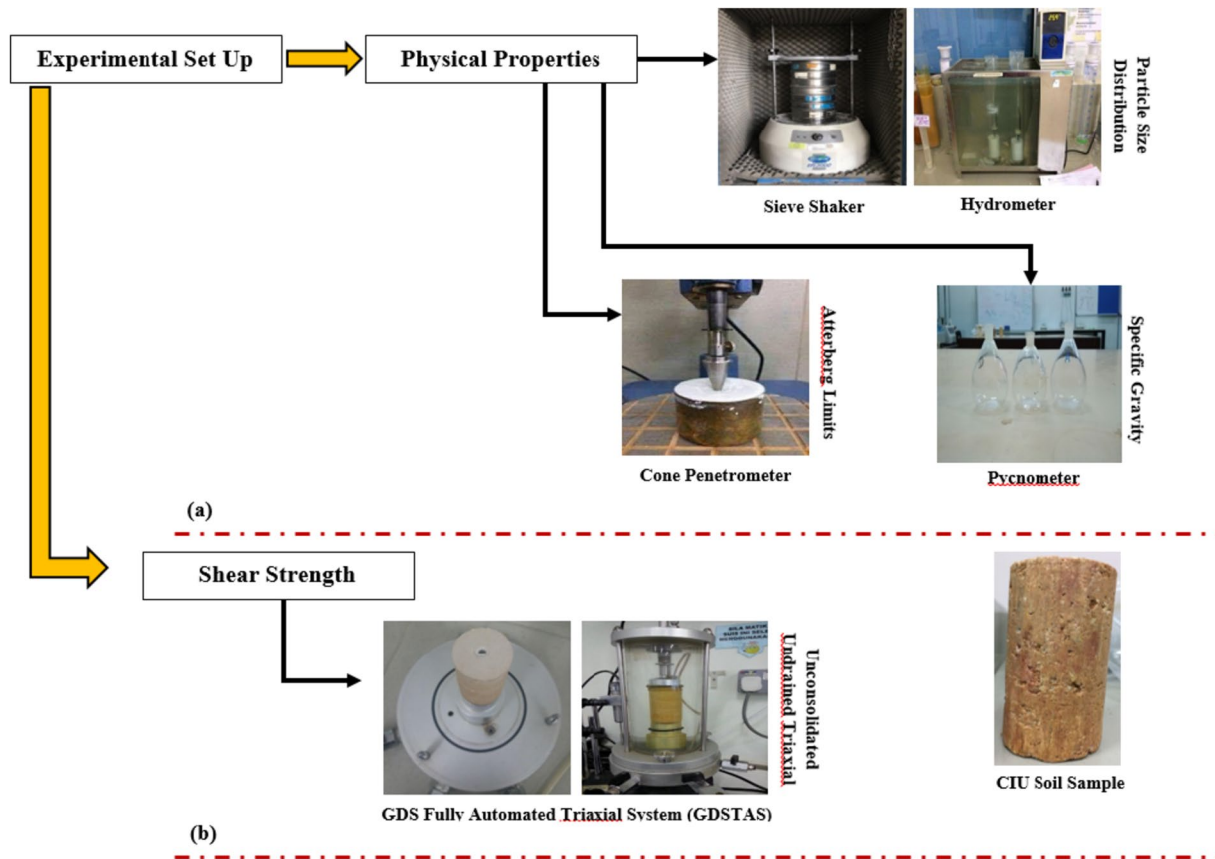


Fig. 2 Experimental set-up to determine physical and strength properties of soil

On-site moisture absorption monitoring

Tensiometers and gypsum moisture blocks are applied with a same configuration to assess moisture absorption in soil with pressures less than 100 kPa and pressures greater than 100 kPa (Zaini et. al., 2020a). The dependability and competence of instruments are critical for representing on-site monitoring data for additional modelling and analysis of gradients. The instrument was accommodated at the slope region and at the flat region as depicted in Fig. 1. Each tensiometer station was situated 1.1, 2.2, and 4.4 m from the tree and with a depths of 0.25, 0.5, 1.0, 1.5, and 2.0 m as depicted in Fig. 3. The calibration testing was carried out to ensure the instrument's reliability and capability to record soil matric suction.

The gypsum block was used to quantify suction over 80 kPa and up to 1000 kPa. The tensiometers and gypsum blocks with a depth of 0.25, 0.5, 1.0, 1.5, and 2.0 m were set-up near the trees at the slope crest, as depicted in Fig. 3. According to Biddle (2001), each station (F.A. 1, F.A. 2, FA3, S.A. 1, S.A. 2, and S.A. 3) was placed with a gypsum blocks. The matric suction value was evaluated by observing the data via electrical resistivity and soil moisture.

Besides, to measure the in situ soil matric suction, 30 Jet-fill Tensiometer Model 2725 units were deployed at varied depths of 0.25, 0.5, 1.0, 1.5, and 2.0 m. Rees and Ali (2012) proved that variations of the moisture content in the tree vicinity and the effect of the root geomorphology was strongly associated to a 2.0 m depth. Therefore, it is estimated that the installed tensiometers at 2.0 m depth will be sufficient to assess changes in tree moisture absorption in the research area.

The rain gauge bucket was put up on a tripod mount to offer a plane platform for rain gauge set-up to deliver a perfect reading. To analyse the continuous precipitation rate, a Rainew model (see Fig. 3) was set-up in the research region. In most circumstances, 8000 data points, equivalent to 1600 mm of total precipitation, may be documented. The hydrologger was placed at the slope base, and the precipitation was recorded for every 15 min. For 8 months, rainfall data were obtained once every month. During this recording period, the calibrated technique was used to ensure that the rain gauge was operating properly.



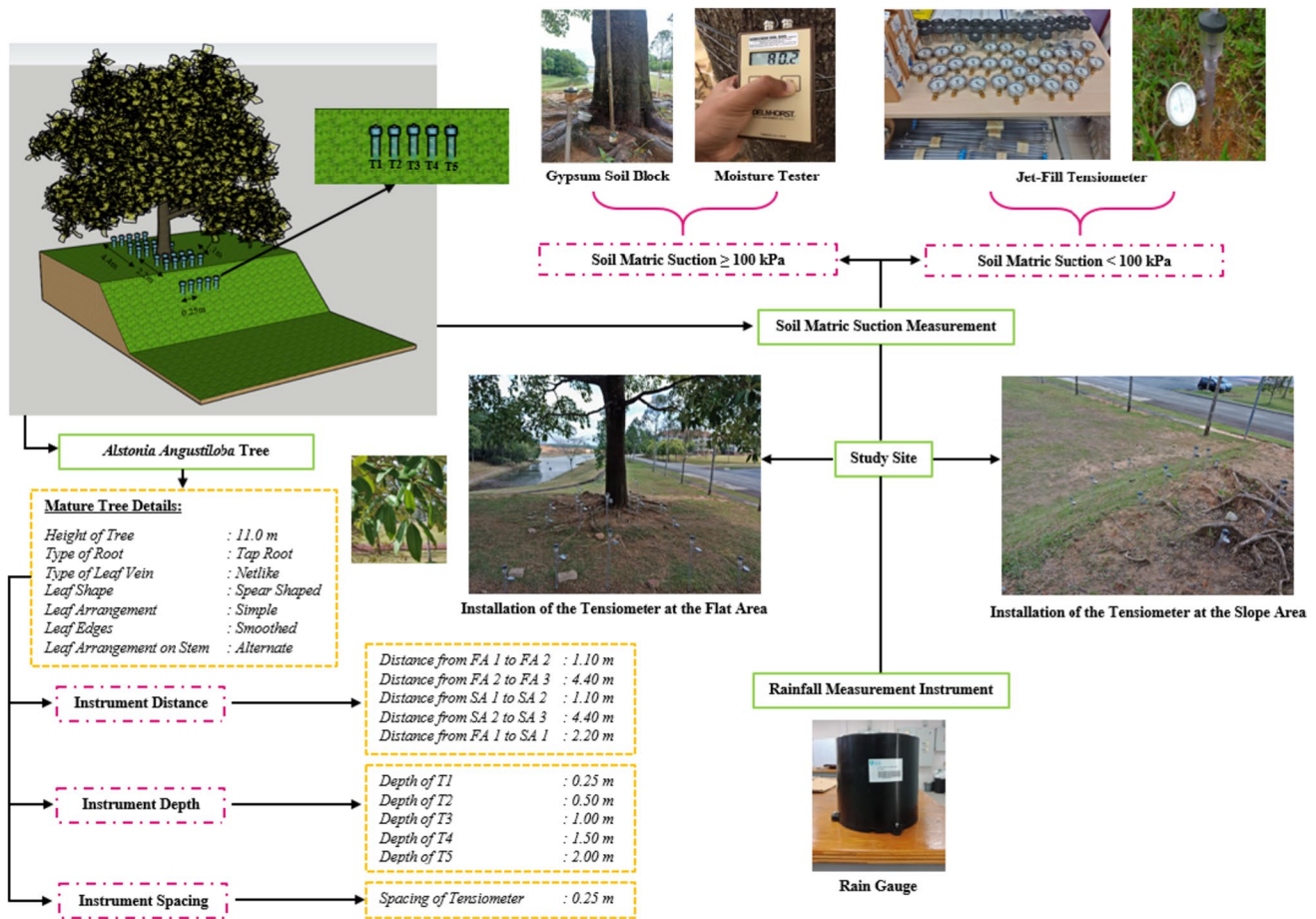


Fig. 3 Experimental set-up for on-site monitoring

Development of soil suction profile at the root-dynamic region

The contour plots for 2D and 3D soil matric suction were created using GiD software and Surfer software. These plots were generated by inputting information about materials, geometry, parameters, and solution details. The software utilized finite element meshing and mathematical simulation to represent the slope geometry of the unsaturated slope. Subsequently, on-site monitoring data collected over 8-month period were incorporated into the software. The resulting outputs, presented in Figs. 13 and 14, visualize the analysis of tree moisture absorption.

Evaluation of unsaturated slope stability

To evaluate the slope stabilization and its resistance to unfavourable soil moisture pore pressure caused by tree moisture absorption, specific input data must be supplied to apply the relevant equations. The assessment of slope strength involved several steps based on the approach presented by Fredlund

and Rahardjo (1993): (1) conducting a survey to determine the geometry of the slope and thoroughly investigate the selected slope surface; (2) carrying out a detailed investigation to identify the stratigraphy of the rock/soil and collect undisturbed soil samples for testing; (3) determining suitable shear strength parameters that represent the shear strength of soil through laboratory testing; and (4) measuring the unfavourable pore moisture pressure above the groundwater table. Additionally, the study took into account the unvegetated fully saturated slope.

The SLOPE/W software version 7.03 from 2007 was employed to perform initial checks on the slope stability results and compare them with the previous approach equation. Additionally, the software was used to determine the critical slip surface through a trial and error process. A total of 64 potential failure surfaces were assessed to identify the critical slip surface, as illustrated in Fig. 4. Equation 1 was applied to assess the weight of the soil involved. The actual slope calculations were carried out considering the movement of the slip surface across the slope crest, and the position and elevation of each section are depicted in Fig. 4.

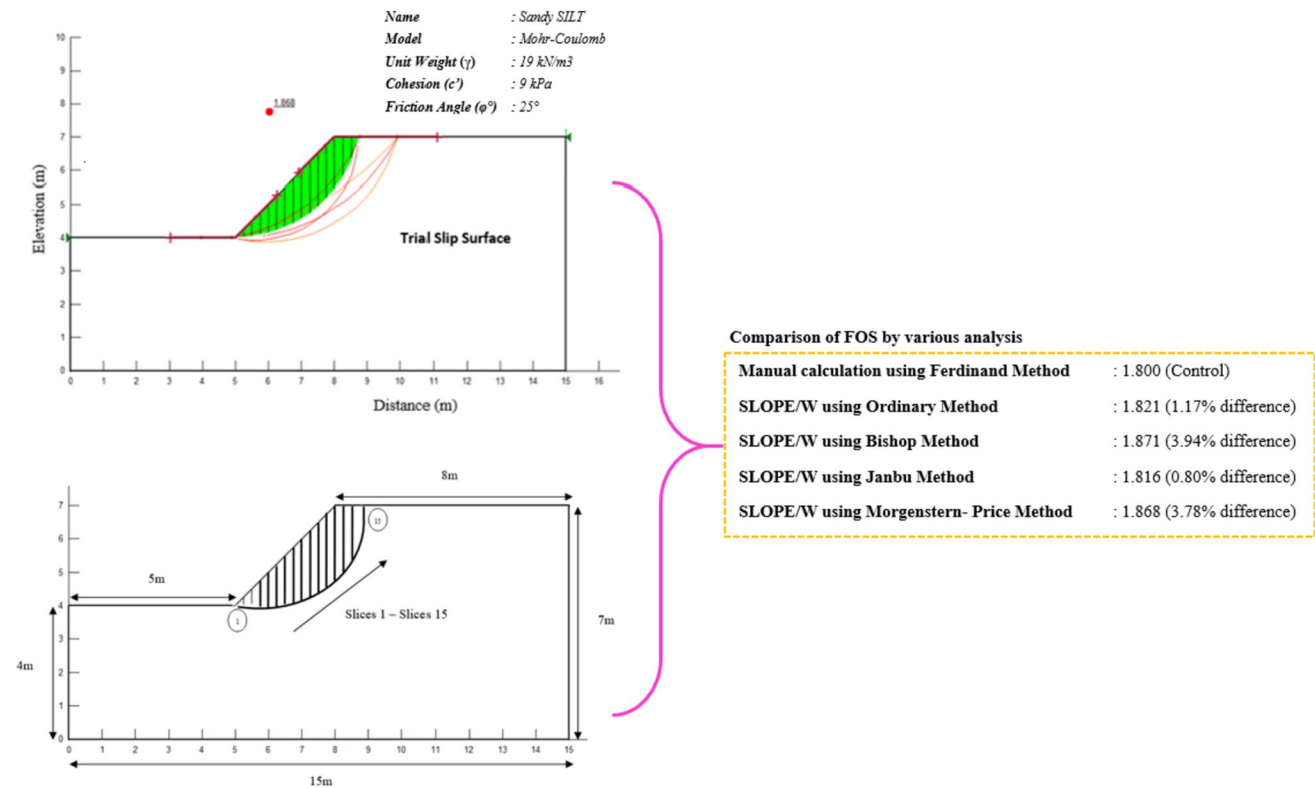


Fig. 4 Unsaturated slope geometry and comparison of FOS by multiple analysis

$$F = \frac{(\sum c' l R + (W \cos \beta) R \tan \phi' + S R l \tan \phi^b)}{\sum W R \sin \beta} \quad (1)$$

where ϕ^b is the internal friction angle of the unsaturated soil, ϕ' is the internal friction angle of the saturated soil, β is the angle between the tangent to the centre of the base of each slice and the horizontal, W is the surcharge load (kN), R is the radius of circular failure surface (m), l is the slip arc length, and c' is the cohesion. Using the traditional method of slices in the software, the lowest safety factor (FOS) value of 1.868 was determined. To compare and analyse the dissimilarities and variations in FOS with other adopted techniques, the FOS value of 1.87 was used as a reference point. The exact slip surface corresponding to this FOS value had a radius of 3.9 m and an origin at coordinates $x=5.0$ m, $y=7.9$ m on the unsaturated slope composed of low residual soil. The calculated slip surface was compared with various techniques available in the Geostudio software. Figure 4 illustrates the discrepancy between these different techniques. The discrepancy margin between Eq. 1 and the ordinary method (Fellenius Method—SLOPE/W) was minimal because these two methods were derived from very similar formulas and approaches.

Statistical analysis

Mathematical analyses were analysed using Statistical Package for the Social Sciences (SPSS) software. One-way analysis of variance (ANOVA) was employed to examine the relationship between soil suction and precipitation. Fisher's least significant difference (LSD) test was utilized to quantify substantial discrepancies between mean values, with a significance level set at $p < 0.05$. Moreover, Pearson's correlation analysis was performed to assess the correlations between precipitations, the space interval between tensiometers, station area, and slope depth.

Results and discussion

Physical properties of soil

The primary physical properties examined included consistency limits, specific gravity, and sieve analysis. Based on the BS standard, the soil was categorized as sandy SILT (MVS) soil with very high plasticity. The sieve analysis results for a 100 g soil sample showed that 4.2% of the soil particles were larger than 2 mm (gravel), 28.0% fell within the range of 2 to 0.063 mm (sand), 45.0% ranged from



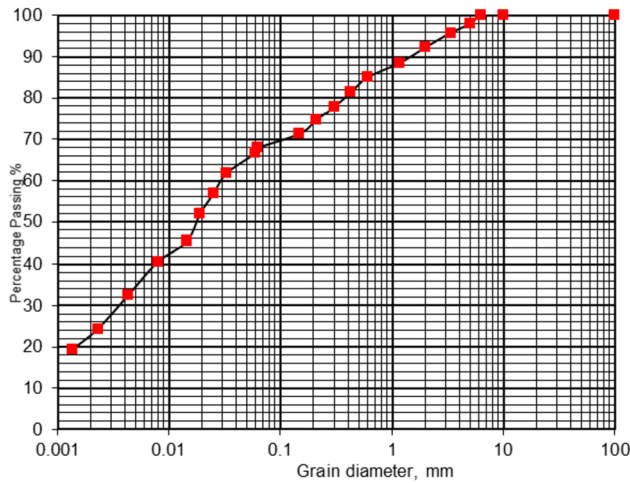


Fig. 5 PSD graph of the soil

Table 1 Unsaturated friction angle, ϕ^b of the soil obtained by various researchers

References	State	ϕ' (°)	ϕ^b (°)
Author	Pahang	25.0	21.0
Rahardjo et.al. (2004)	Singapore	25.1	24.3
Huat et.al. (2005)	Selangor	26.0	26.0
Zolkepli et.al. (2018)	Pahang	25.0	17.0
Ishak et.al. (2021a)	Johor	23.0	20.0

0.063 to 0.002 mm (silt), and 23.0% were smaller than 0.002 mm (clay). Figure 5 illustrates the PSD of the unsaturated slope's soil. Additionally, the Atterberg limits of

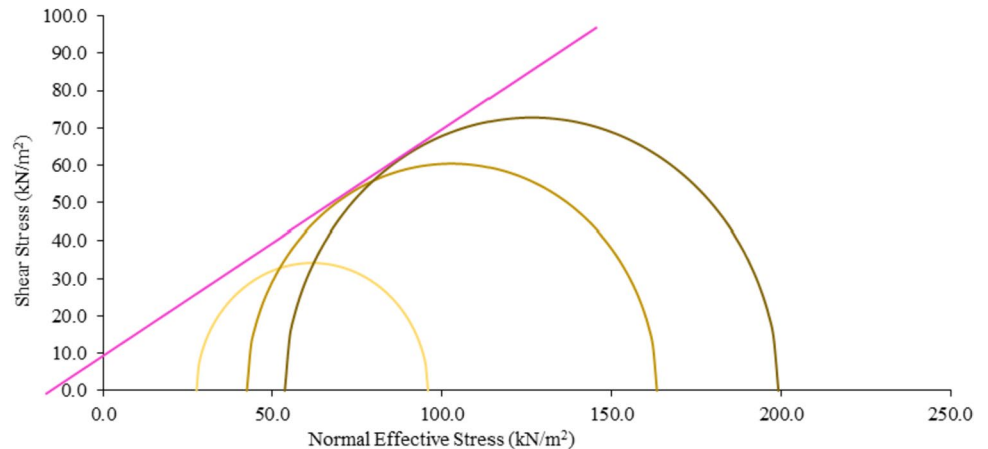
the soils indicated a liquid limit (L.L.) of 70.0%, a plastic limit (P.L.) of 31.0%, and a plasticity index (P.I.) of 39.0%. Based on BS standards, the soil can be classified as high plasticity SILT (MHS), with a specific gravity of 2.74. As noted by Zolkepli et al. (2018), the specific gravity of the soils can vary widely due to extensive metallurgical modifications. The physical property values acquired align with the study conducted by Zolkepli et al. (2019) and Zolkepli et al. (2021b) in their respective investigations.

Shear strength parameters of soil

According to Zaini et al., (2020a) and Ishak et al. (2021b), the most recent unsaturated friction angle (ϕ^b) is consistently similar to or smaller than the saturated friction angle (ϕ'). Besides, soil shear strength is proportional to tree moisture absorption, with ϕ^b being equal to ϕ' when the tree moisture absorption is less than the air-entry value (Rees & Ali 2012). The shear strength values for the unsaturated friction angle (ϕ^b) obtained by various researchers are highlighted in Table 1. The findings in Table 1 can be assumed that the ϕ^b is smaller than or equal to the ϕ' as conducted by the previous researchers.

In cases of higher tree moisture absorption, the unsaturated friction angle (ϕ^b) tends to reduce to a lower value. Consequently, an increase in matric suction leads to the expulsion of more moisture from the soil's pores without a corresponding increase in net stress (Zolkepli et al. 2019). Figure 6 depicts Mohr's circle and the failure envelope for three specimens used, illustrating the effective friction angle (ϕ') as 25 degrees and the effective cohesion (c') as 9 kPa.

Fig. 6 Effective stress failure envelope of the unsaturated soil



Influence of rainfall event to the soil suction dispensation arrangement

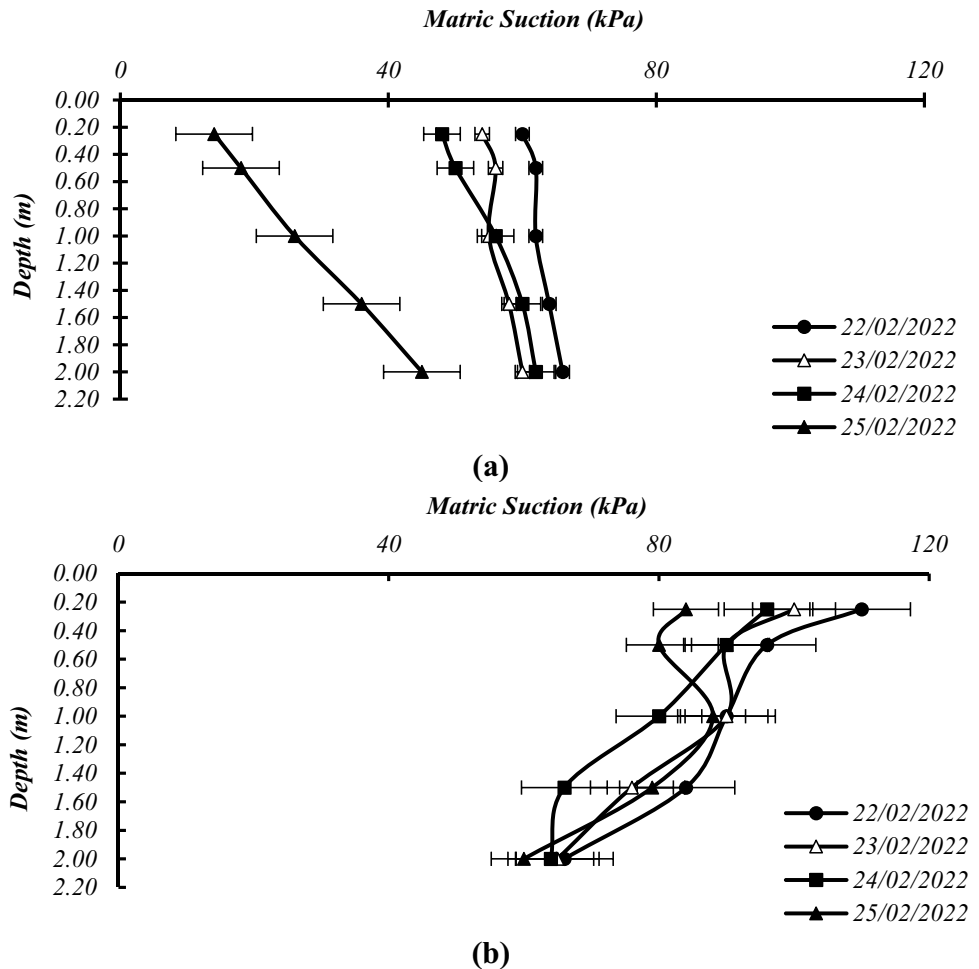
Influence of intense rainfall on the soil suction dispensation arrangement

Various researchers, including Yue et al. (2019), Goh et. al. (2020), Zaini et al. (2020a), and Ishak et al. (2021a), have conducted investigations on the response of tree moisture absorption to a single rainfall arrangement on slopes, with a focus on reducing the observation period. Their studies aimed to isolate specific precipitation arrangements during observation intervals, as various arrangements often involve intense and prolonged rainfall. In line with this, the tree moisture absorption arrangements observed on the low residual slope, both without with the presence of *Alstonia Angustiloba* tree, aligned with the findings of previous researchers. A comparison was made between vegetated and unvegetated slope. During the on-site observation from early February 2022 to the end of March 2022, the unvegetated slope experienced the withered conditions, with no rainfall

for 11 consecutive days. As a result, the maximum recorded suctions were 59 kPa (at 0.25 m depth), 61 kPa (at 0.50 m depth), 61 kPa (at 1.00 m depth), 63 kPa (at 1.50 m depth), and 65 kPa (at of 2.00 m depth). These results demonstrate that even during extended dry periods, the maximum tree moisture absorption value for the soil was 65 kPa. However, an intense and brief tropical precipitation event on 24 February 2022 caused a significant decrease in tree moisture absorption at 0.25 to 2.0 m depth, as depicted in Fig. 7.

In Fig. 7a, the average tree moisture absorption arrangements on the unvegetated slope demonstrate that considerable tree moisture absorption can occur during prolonged dry periods. However, the short and intense rainfall events quickly dissipate the tree moisture absorption. Hence, at this point, the soil moisture pore pressure did not achieve positive values at any depth. The average tree moisture absorption arrangement on the unvegetated slope indicates that significant tree moisture absorption was rapidly dispersed by a precipitation event of 8.4 mm on 24 February 2022. This resulted in the suction pattern at various depths dropping to minimum values of 15, 19,

Fig. 7 Soil matric suction concerning the intense rainfall precipitation at **a** unvegetated slope and **b** vegetated slope



27, 37, and 46 kPa at various depths. During a prolonged dry period followed by intense rainfall events occurring for approximately 11 days, the highest tree moisture absorption was remarked at the unsaturated slope crest where the *Alstonia Angustiloba* tree was present. At various depths, the tree moisture absorption values were 112, 98, 92, 86, and 68 kPa. These findings indicate that the most significant tree moisture absorption value for the soil is 112 kPa. After the intense precipitation event, the tree moisture absorption decreased and only reached the lowest value on the slope with a tree.

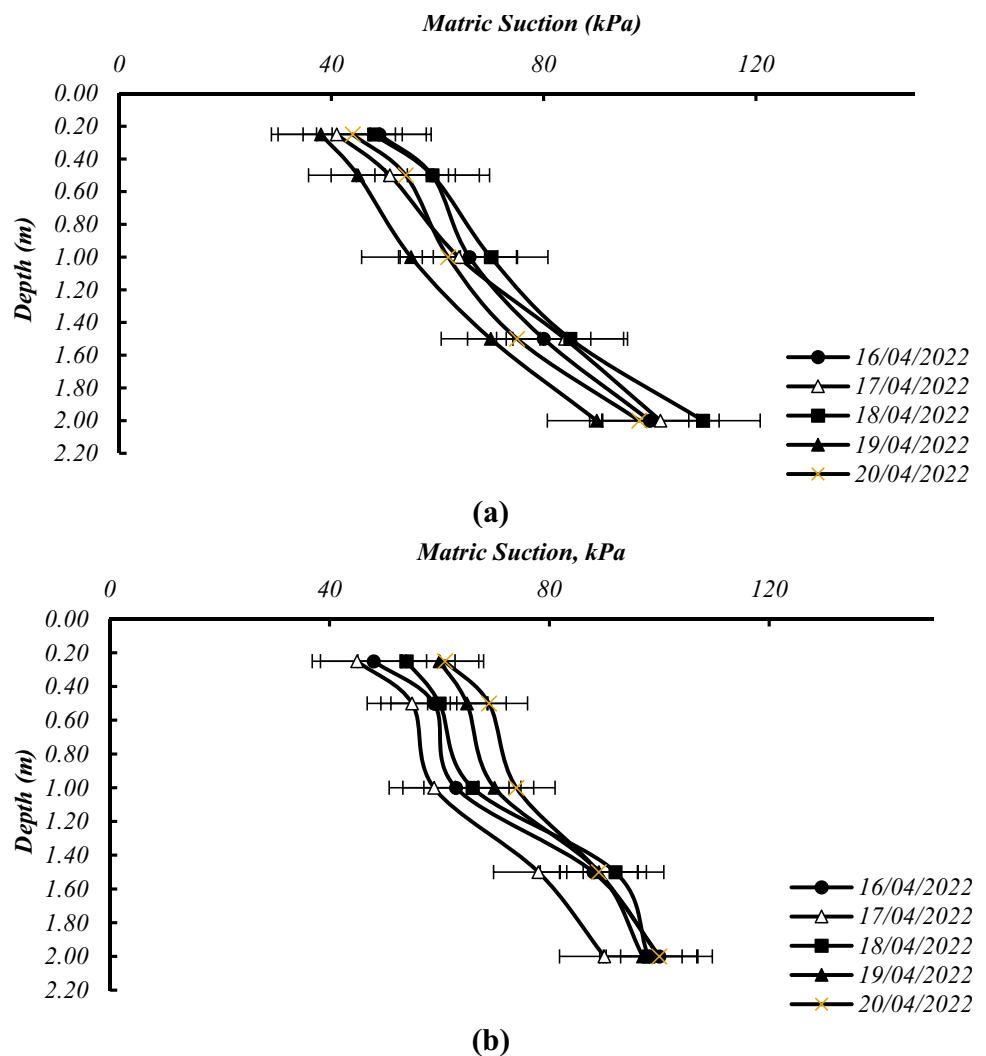
At 0.25 and 0.5 m depth, the tree moisture absorption decreased from 112 to 82 kPa and from 98 to 78 kPa. However, at a depth of 1.0 m, the tree moisture absorption remained relatively unchanged, decreasing only slightly from 91 to 89 kPa. Eventually, the matric suction decreased to lower values, from 85 to 78 kPa at a depth of 1.5 m and from 67 to 59 kPa at a depth of 2.0 m. The tree

moisture absorption at shallow depths was more sensitive to intense precipitation events compared to a deeper depth which were not significantly affected. Despite both slopes receiving the same amount of precipitation, the differences in tree moisture absorption responses were observed on the vegetated slope (refer to Fig. 7b).

Influence of antecedent rainfall on the soil suction dispensation arrangement

The tree moisture absorption exhibits periodic variations during dry periods, primarily influenced by the fluctuation in solar radiation between day and night. This suggests that besides precipitation infiltration, other environmental factors such as wind, climate, humidity, and solar radiation can also affect tree moisture absorption. During a moderate rainfall event on 18 April 2022, the suctions at various depths slowly decreased. Figure 8a and b illustrates the profiles of

Fig. 8 Soil matric suction concerning the antecedent rainfall precipitation at **a** unvegetated slope and **b** vegetated slope



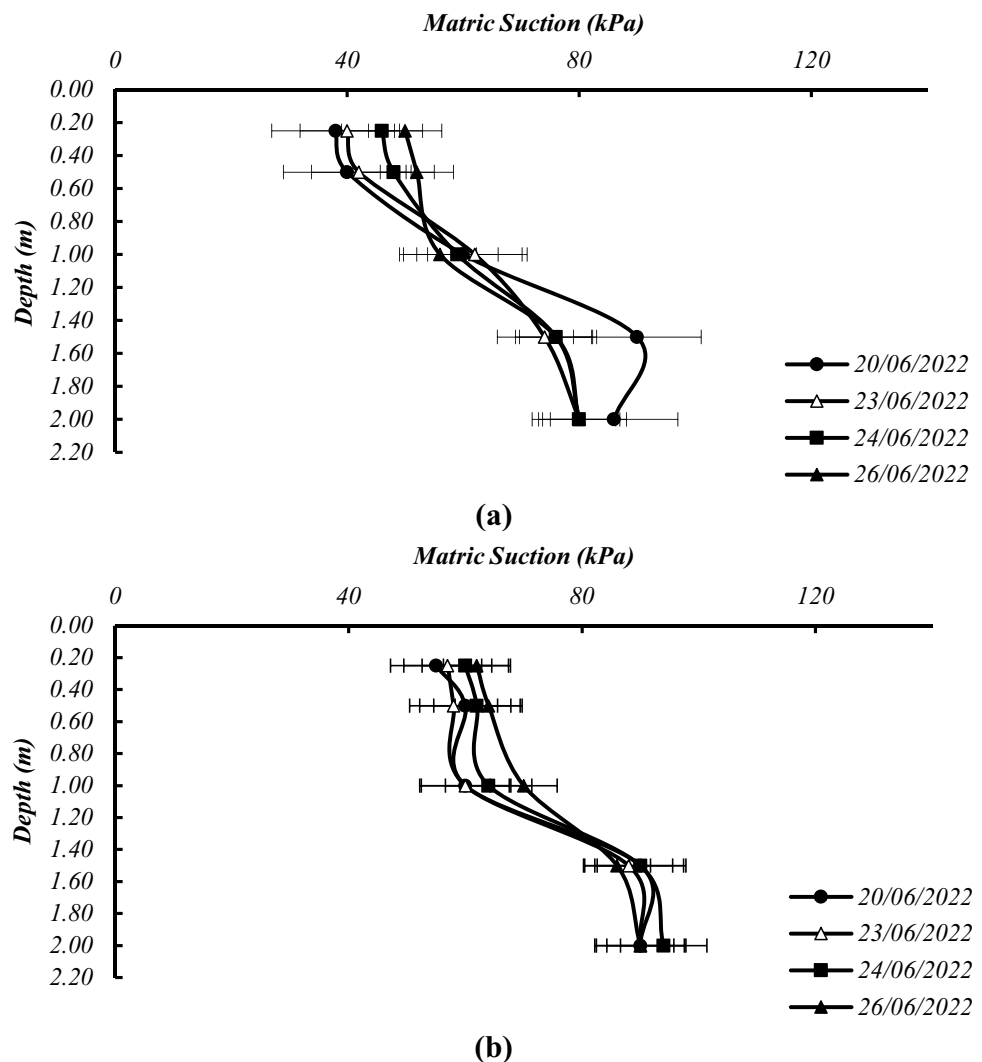
tree moisture absorption on the vegetated and unvegetated slope following previous rainfall events. The tree moisture absorption at a deeper depth was primarily influenced by the intense rainfall on 20 April 2022. These findings emphasize the importance of rainfall patterns for both slopes in determining water infiltration dynamics. Moreover, the arrangements indicate that the continuous low-precipitation from 17 April to 18 April 2022 did not significantly reduce the matric suction. However, the rainfall occurring from 18 April to 19 April 2022 had significant effects on the distribution of suction at depths of 0.25 to 1.0 m.

Furthermore, the comparison of the precipitation arrangement as depicted in Fig. 8 demonstrates a consistent similarity in the distribution pattern of suction between the two slopes. This indicates that the presence of a canopy had negligible influence due to the moderate and previous intense rainfall events, resulting in no substantial dispersion in tree moisture absorption between the vegetated slope and unvegetated slope.

Influence of prolonged antecedent rainfall on the soil suction dispensation arrangement

During the continuous precipitation period from 20 June 2022 to 26 June 2022, the vegetated and unvegetated slopes experienced significant reductions in tree moisture absorption due to the larger precipitation levels, as depicted in Fig. 9a and b. The combination of intense and previous precipitation events led to the insignificant tree moisture absorption at depths of 0.25 to 1.0 m on 23 June 2022, coinciding with the highest rainfall amount on 20 June 2022 (60 mm/day). These results indicate that the smallest tree moisture absorption in the soil was influenced by the intensity of precipitation in conjunction with the antecedent rainfall. At various depths, the soil moisture pore pressure did not achieve a saturated state with a value of 0 kPa. Therefore, the presence of the canopy had minimal impact as the moderate and previous intense precipitation events allowed rainwater to reach the soil beneath the tree's canopy (*Alstonia Angustiloba*).

Fig. 9 Soil matric suction concerning the prolonged antecedent rainfall precipitation at **a** unvegetated slope; **b** vegetated slope



During the extended period of wet weather, the matric suction reduced owing to the high moisture content in the soil. There were no substantial discrepancies recorded in matric suction between the areas near the tree and the unvegetated slope. However, throughout the period without precipitation, the matric suction on the unvegetated slope gradually increased while the matric suction on the vegetated slope increased significantly. The *Alstonia Angustiloba* tree facilitated tree moisture absorption and effectively remove moisture from the soil. Consequently, the dry condition resulted to the matric suction near the tree was significantly higher than the tree moisture absorption at different distances from the mature tree.

Influence of prolonged dry condition on the soil suction dispensation arrangement at discrete stations

The on-site monitoring conducted for 8 months revealed the response of suction arrangement to multiple precipitation distributions. The amount of precipitation played a

significant role in altering water intake on slopes without trees, whereas slopes with trees at the top were less affected. The presence of tree canopies acted as a factor in modifying tree moisture absorption on slopes by reducing the moisture content in the soil. The antecedent and prolonged rainfall were classified as the primary factors influencing suction variations on both slopes. During a time interval of no rainfall from 13 February 2022 to 22 February 2022, following the antecedent and prolonged precipitation, the tree moisture absorption arrangements were recorded for both slopes as depicted in Fig. 10a and b. The data recorded on 13 February 2022 served as the baseline for the insignificant matric suction value, representing the initial condition.

Figure 11a and b reveals the continuous increase in matric suction values after a period of 11 days without rainfall. The dry period exposure led to a substantial increase in tree moisture absorption at a depth of 2.0 m from the slope crest. Furthermore, the highest matric suction values were recorded at S.A. 1 and F.A. 1, specifically at 0.25 and 0.5 m depth, respectively. The suction values were 66 and 56 kPa

Fig. 10 Soil matric suction concerning the prolonged dry condition on 13 February 2022 in **a** slope area and **b** flat area

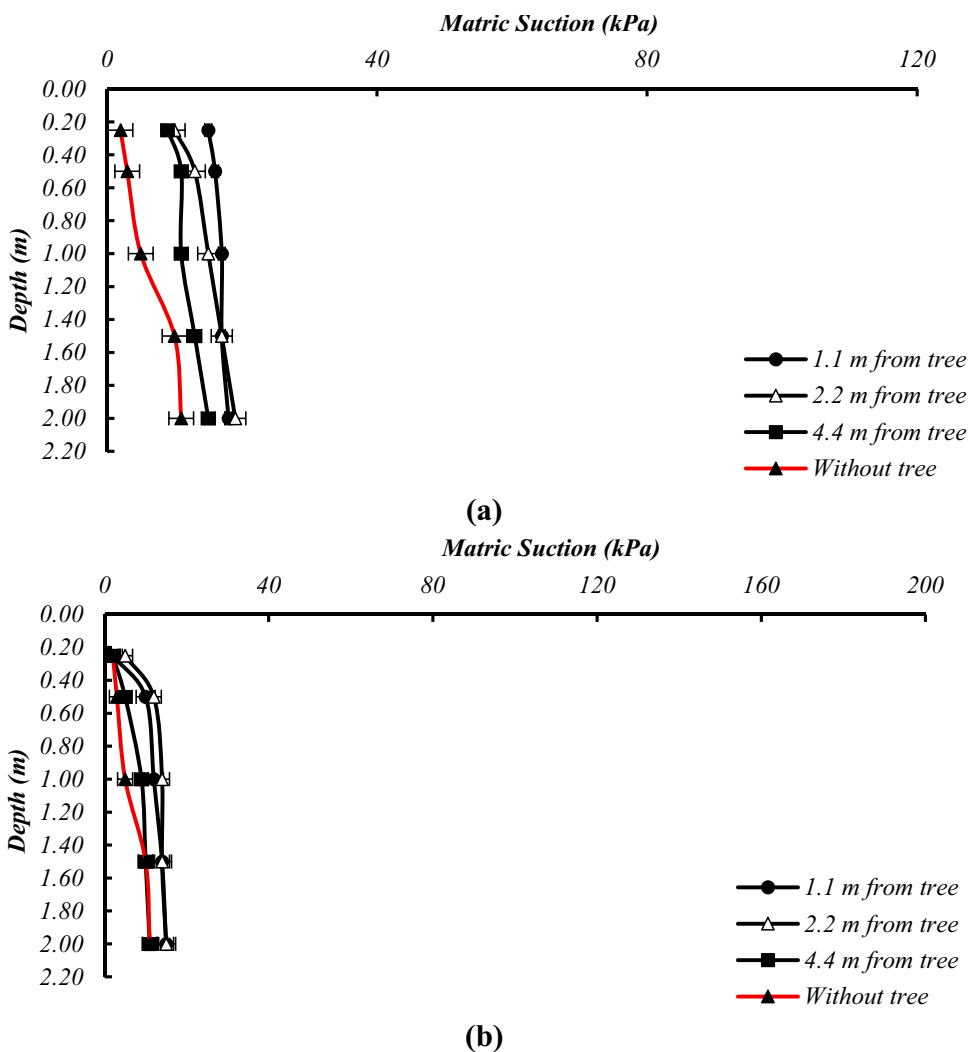
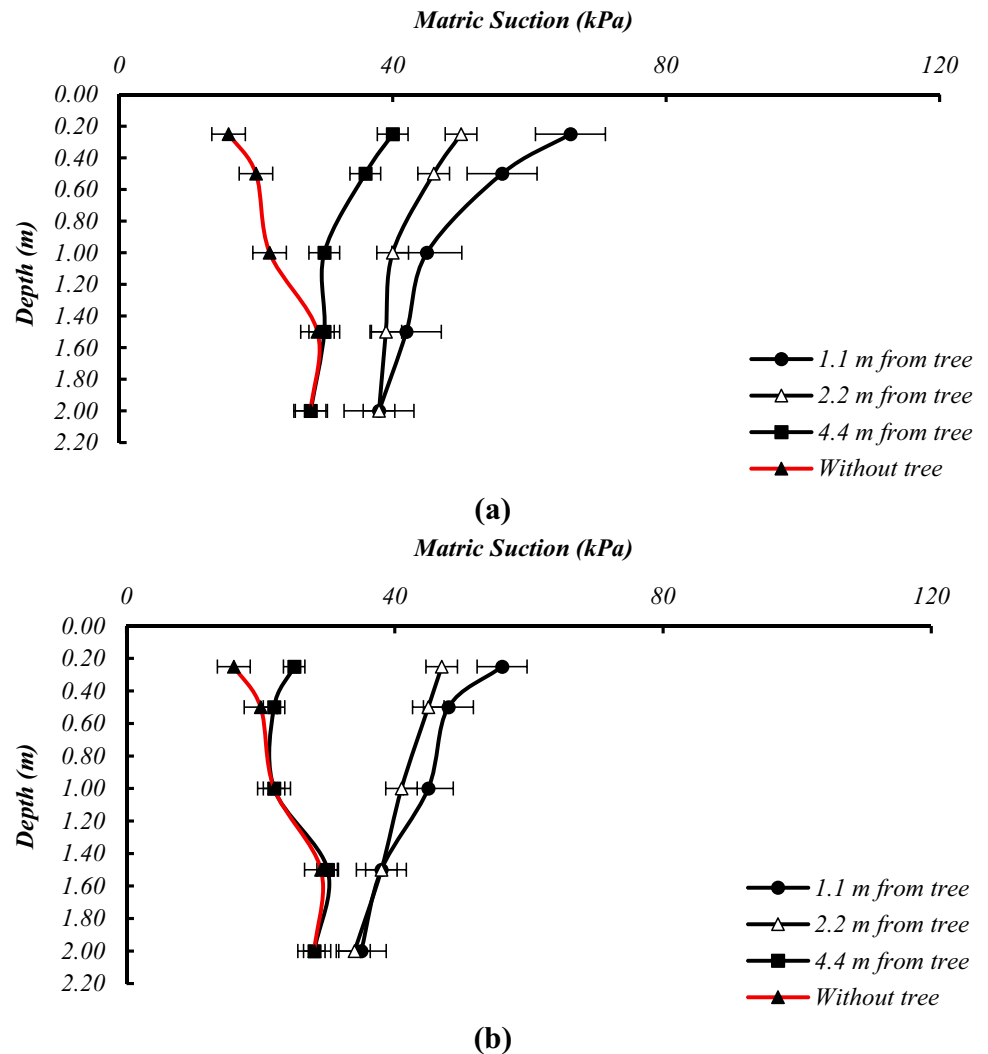


Fig. 11 Soil matric suction concerning the prolonged dry condition on 18 February 2022 in **a** slope area and **b** flat area



at S.A. 1, and 56 and 48 kPa at F.A. 1, respectively, in comparison with the slope without a tree.

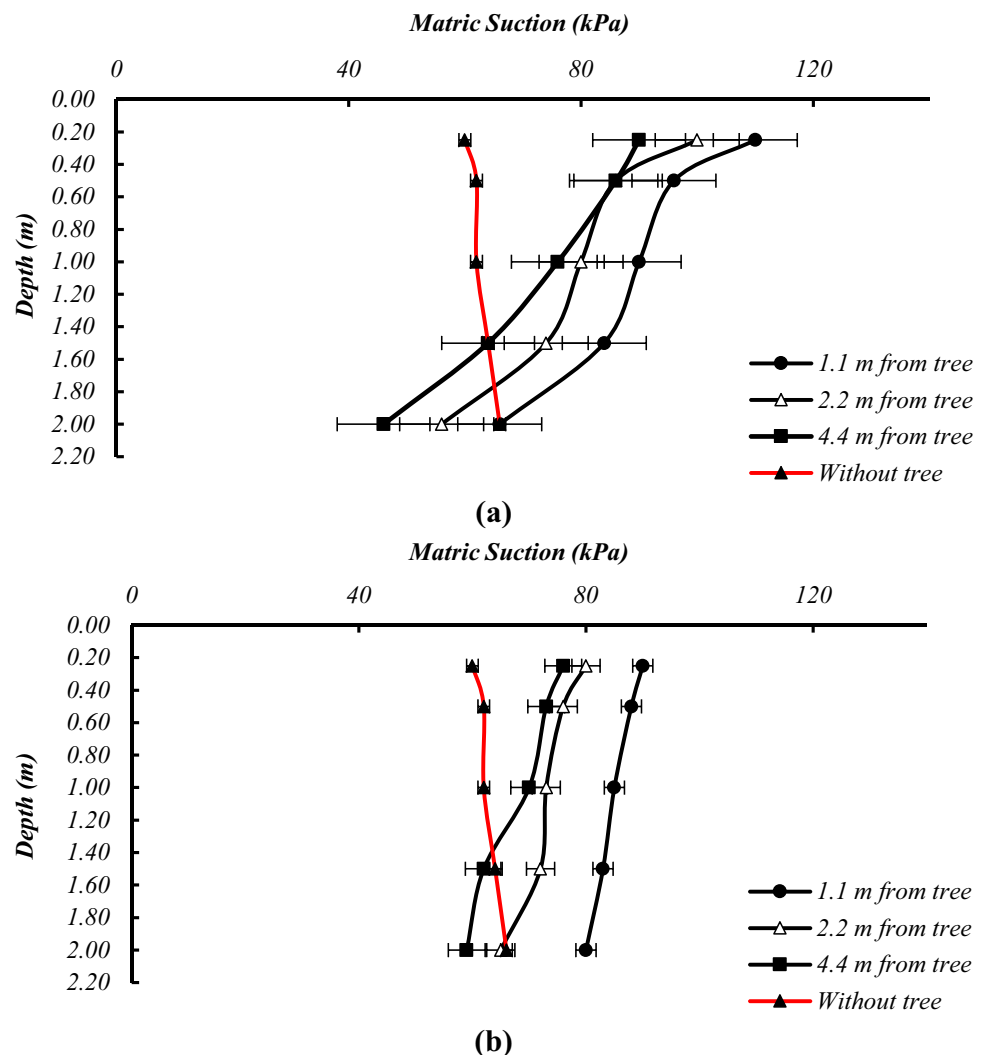
On 22 February 2022, the collected data depicted in Fig. 12a and b demonstrate the highest tree moisture absorption values during the dry condition. The distribution and variations in tree moisture absorption were observed in different locations. Following a period of 11 days without precipitation, the tree moisture absorption at the crest of the slope (2.0 m depth) consistently increased towards the right. Additionally, at a nearest distance (1.1 m) from the *Alstonia Angustiloba* mature tree, the tree moisture absorption at S.A. 1 and F.A. 1, specifically at 0.25 and 0.5 m depth, was higher compared to the unvegetated slope. The matric suction values recorded were 112 and 94 kPa at S.A. 1, and 92 and 86 kPa at F.A. 1.

Previous studies conducted by Zhu & Zhang (2015) and Feng et al. (2021) included a matric suction comparison between the two slopes. The investigation involved tree

moisture absorption in soil columns with and without vegetation, both on-site and in the soil laboratory. The findings revealed that the tree moisture absorption in the vegetated soil columns was significantly larger than in the barren soil columns, indicating the importance of vegetation in enhancing moisture absorption. In the case of the unvegetated slope, the evaluated tree moisture absorption was primarily attributed to the evaporation process, which was smaller compared to the vegetated slope where transpiration played a significant role. Figure 13a and b clearly demonstrates that the distribution of tree moisture absorption at a nearer distance from the tree (1.1 m) was considerably larger than the other distances on the unvegetated slope. Furthermore, the comparison of matric suction arrangement between S.A. and F.A. on 13 February 2022 and 22 February 2022 indicated that the tree moisture absorption at S.A. was larger than at F.A., which can be attributed to the lateral active root growth that was more concentrated at S.A.



Fig. 12 Soil matric suction concerning the prolonged dry condition on 22 February 2022 in **a** slope area and **b** flat area



Delineation of on-site moisture absorption monitoring corresponding to the various rainfall events

The model consisted of 86 mesh elements with 90 vertex for the 2D model and 120 nodes for the 3D model. Matric suction values were assigned to each mesh element and node to represent the moisture migration pattern influenced by a single mature tree. The assumed root region extended to 2.0 m depth and 4.4 m radial distance symmetrically from the tree's focal point. This lateral and vertical extension of the root region resulted in drying arrangements from the base of the tree to the slope crest. The lowest recorded moisture absorption values were 56 at 0.25 m depth and 60 at 0.5 m depth recorded on 13 February 2022 after antecedent rainfall event.

The results of on-site monitoring on 18 February 2022 were used to apply the tree moisture absorption on the mesh

model as depicted in Fig. 13. This model demonstrated the changes in tree moisture absorption and soil moisture loss in the vicinity of the mature tree. Figure 13 also highlights an extraordinary suction of 80 kPa at the base of the *Alstonia Angustiloba* tree on the slope. Figure 14 displays the tree moisture absorption on 22 February 2022, revealing a rapid increase in tree moisture absorption compared to 18 February 2022. The highest moisture absorption value of 112 kPa was observed at the base of the tree on the slope's highest point, while the lowest moisture absorption value was 64 kPa. The drying conditions for 11 days resulted in the development of the soil suction contour, indicating that the observed slope's soil suction decreased with increasing distance from the tree. As stated by Hongde et al., (2021), the suction of the soil significantly reduced after several days of antecedent rainfall due to high precipitation infiltration. The presence of the single mature tree helped to increase the matric suction, leading to higher moisture extraction from the soil.

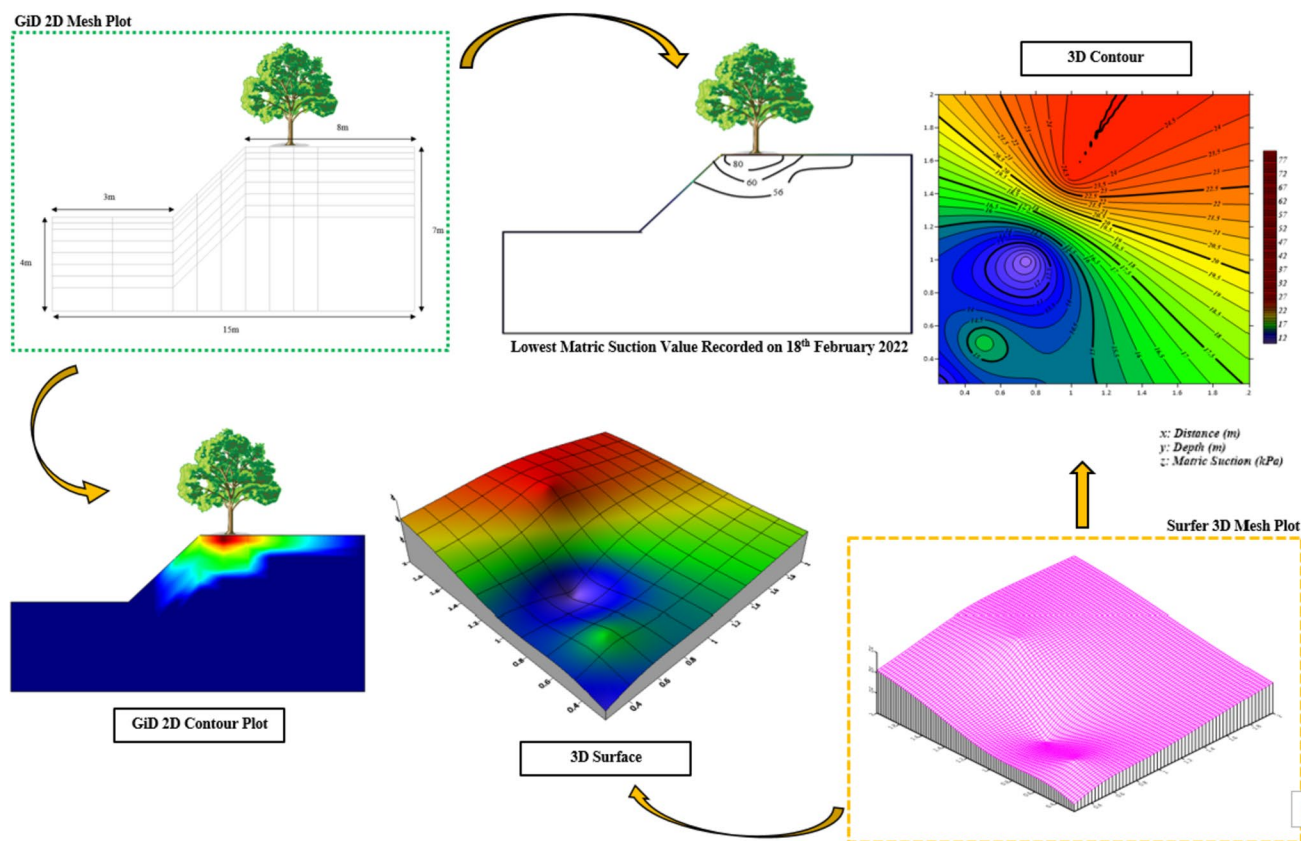


Fig. 13 Lowest soil matric suction (kPa) contour

Influence of soil matric suction on the unsaturated slope stabilization

The ϕ^b angle played a significant role in the increment of tree moisture absorption. This parameter also had a considerable influence on the calculation of the FOS for the slope, as presented in Table 2. The table demonstrates the variation in the ϕ^b angle with the increment of matric suction. Figure 15a illustrates the response of FOS to various matric suction values for the ϕ^b angle. The increment in FOS is attributed to the increase in matric suction value and ϕ^b angle, as depicted in Figs. 14 and 15. The FOS calculations were conducted using on-site soil suction data corresponding to the highest value observed during the on-site monitoring work. The values of matric suction recorded from the on-site monitoring were used to determine the FOS values of the slope.

In the previous section, the soil suction profiles acquired from the on-site monitoring were utilized to examine the existing slope stability. The arrangements of tree moisture absorption, derived from the on-site observations, were incorporated into the FOS calculations. The critical slip surface location was determined by integrating slices with the soil matric suction (refer to Fig. 15b). The influence of

the transpiration process from the mature tree on the matric suction in the proximity of the tree was considered in the slope stabilization analysis conducted during on-site monitoring. The on-site data imparted valuable insights into the changes in matric suction induced by the drying condition at the slices base of the mature tropical tree. These findings and analyses led to a preferable knowledge on the slope stability dynamics in relation to the matric suction variations influenced by the tree moisture absorption.

In Fig. 16, the discrepancy in the FOS values over the course of on-site monitoring, which includes rainfall precipitation data, is presented. The initial FOS for the saturated slope was 1.868, which was lower than the unsaturated slope without the presence of the *Alstonia Angustiloba* tree. The FOS values showed variations over time and in response to the tree water uptake. In Fig. 16, an increasing trend in the FOS can be observed, characterized by several upward shifts in the line during the drying periods. These drying periods occurred in different time intervals, namely February 2022 to March 2022, May 2022 to June 2022, and July 2022 to September 2022. During these gap, soil moisture loss occurred, resulting in a higher tree moisture absorption. However, the FOS abruptly decreased through the 24-h moisture infiltration due to higher moisture content contains



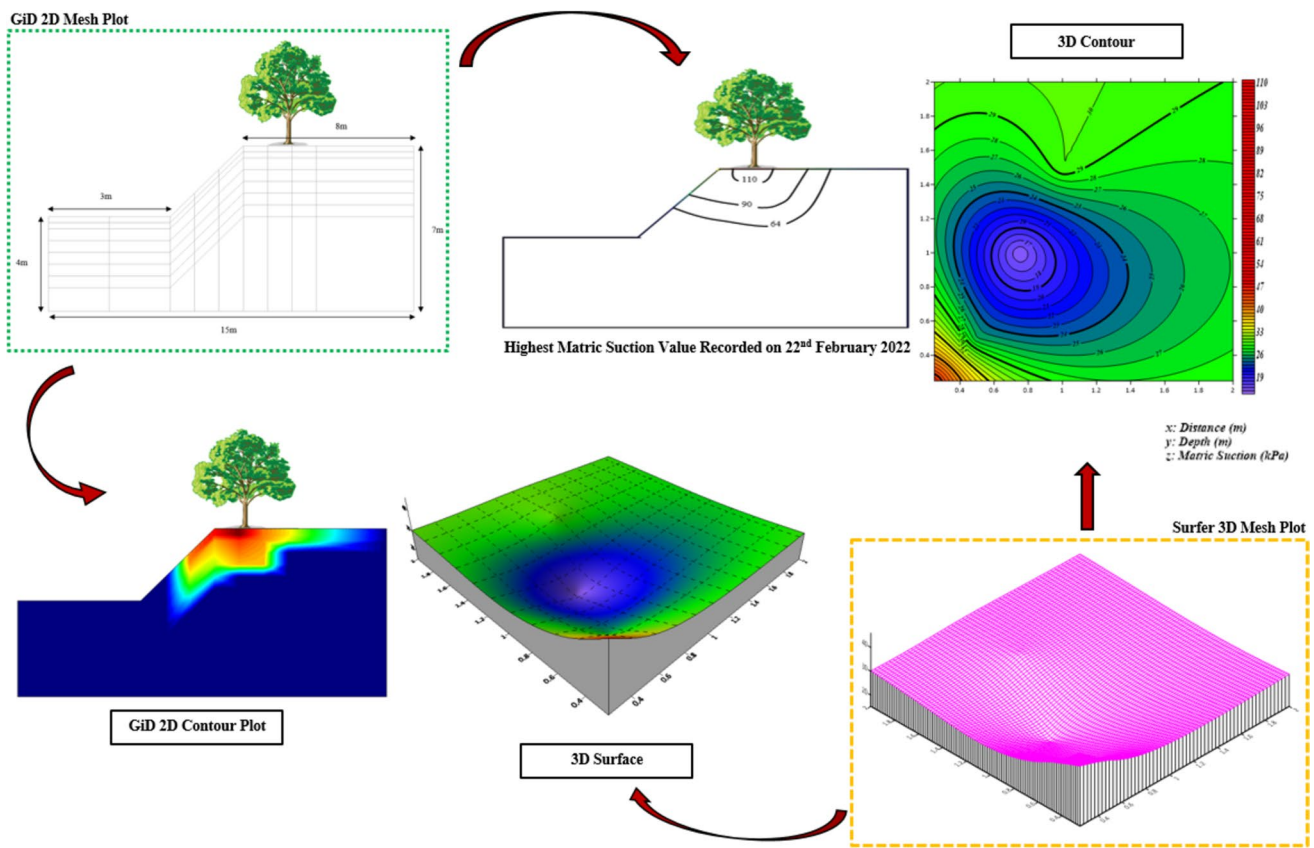


Fig. 14 Highest soil matric suction (kPa) contour

Table 2 Non-linear value of ϕ^b angle

Parameters	Value
Soil type`	Sandy SILT
Unit weight, γ (kN/m ³)	19.0
Unsaturated friction angle, ϕ^b , (°)	At suction of 0–80 kPa At suction of 80–100 kPa At suction of 100–300 kPa
	20.0 14.0 10.0

in the soil. This analysis provides insights into the dynamic nature of the FOS in relation to the tree moisture absorption and rainfall events, highlighting the impact of soil moisture variations on slope stability.

In Fig. 16, it is observed that the FOS value gradually increases in less than 3 weeks after heavy rainfall events through the evaporation process (FOS without tree). This indicates that the FOS value improves over time as the moisture in the soil evaporates. On 19 February 2022, the FOS of the vegetated slope reached 53.00% higher than the FOS of the unvegetated slope. This significant increase in FOS is attributed to the enhanced tree moisture absorption on the vegetated slope, which contributes to the stabilization of the slope. The tree on the slope crest plays a crucial role in expediting the tree moisture absorption after rainfall events. This

tree acts as an active tool for removing moisture from the soil, hence stabilize the soil slope. These findings highlight the beneficial effect of mature tropical trees in enhancing slope stability by facilitating water uptake and drainage in the soil. The presence of trees can effect the stabilization of the slopes, providing a natural means of water management and erosion control.

Prediction of the best safety factor model via multiple regression analysis

The ANOVA analysis conducted in this study shows substantial difference between independent parameters (station area, slope depth, and distance of tensiometers from the tree and rainfall precipitation) at various rainfall events

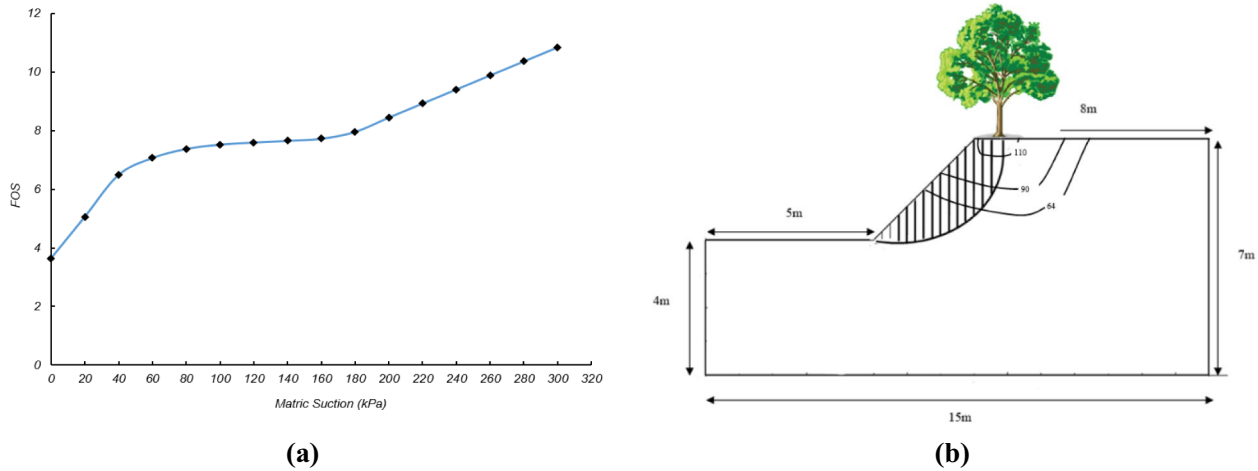


Fig. 15 Interrelation between **a** FOS against matric suction and **b** matric suction with critical slip surfaces

with a p -value of 2.25×10^{-70} ($p < 0.05$). This indicates that the independent variables have a mathematically substantial effect on the observed parameters. LSD analysis was carried out to further investigate which variables lead to the significant discrepancies between the means, and the results are tabulated in Table 3. The LSD test compares the mean differences between pairs of variables and determines if the differences are statistically significant (Ai et al. 2021; Zaini and Hasan 2023c). Based on the LSD analysis, all six conducted analyses accepted the null hypothesis (H_0) as the average difference between the variables was less than the LSD value (0.4147). This means that the statistically significant differences observed in the study can be attributed to specific combinations of parameters. Specifically, the analysis indicates that there is a substantial discrepancy between precipitation and the gap between tensiometer from the tree, as well as between rainfall intensity and the depth of the slope. Additionally, there is a substantial discrepancy between precipitation and the slope station, with mean differences of 5.84, 7.36, and 7.91. These results highlight the effect of precipitation, slope station, tensiometer distance, and depth of the slope on the observed parameters, indicating their importance in understanding and assessing the behavior of the slope under different climate changes.

Based on the LSD analysis, it is observed that there are substantial discrepancies between the tensiometer distance and the sloping depth, as well as between the tensiometer distance and the station area, with mean differences of 1.53 and 2.08. Furthermore, a significant difference is also found between the sloping depth and the station area, with a mean difference of 0.56. In this study, the LSD analysis was utilized to determine which parameters contributed to the significant differences observed in the study, as mentioned earlier. The reference to the usage of LSD by Zaini

et al. (2023a) suggests that these studies also employed the LSD test for mean separation in their respective research. Overall, the results of the LSD analysis provide valuable insights into the relationships and significant differences between the variables examined in this study, aiding in a better understanding of the factors influencing the observed parameters.

Table 4 presents the results of Pearson's correlation coefficient analysis, which was carried out to assess the relationship between the observed parameters. According to Xue et al. (2021), correlation values beneath 0.40 indicate a weak correlation, values higher than 0.40 indicate a strong correlation, and a correlation value of zero indicates no correlation. Based on the correlation coefficients in the table, it can be observed that there is a very weak correlation among the three independent variables. The correlation values approach zero, indicating a lack of significant association between these variables (Zaini and Hasan 2023b). However, it should be noted that the station area variable does not exhibit any correlation with the other variables. It is important to understand that correlation analysis provides insights into linear relationships between variables but does not establish causation or capture the full complexity of interactions among the variables. Therefore, the weak correlations observed in this study suggest minimal linear associations among the variables, except for the station area, which does not show any correlation with the other parameters.

Conclusion

This study investigates how the presence of a single mature tree at the crest of a slope affects the distribution of tree moisture absorption in soil. The profile of tree moisture



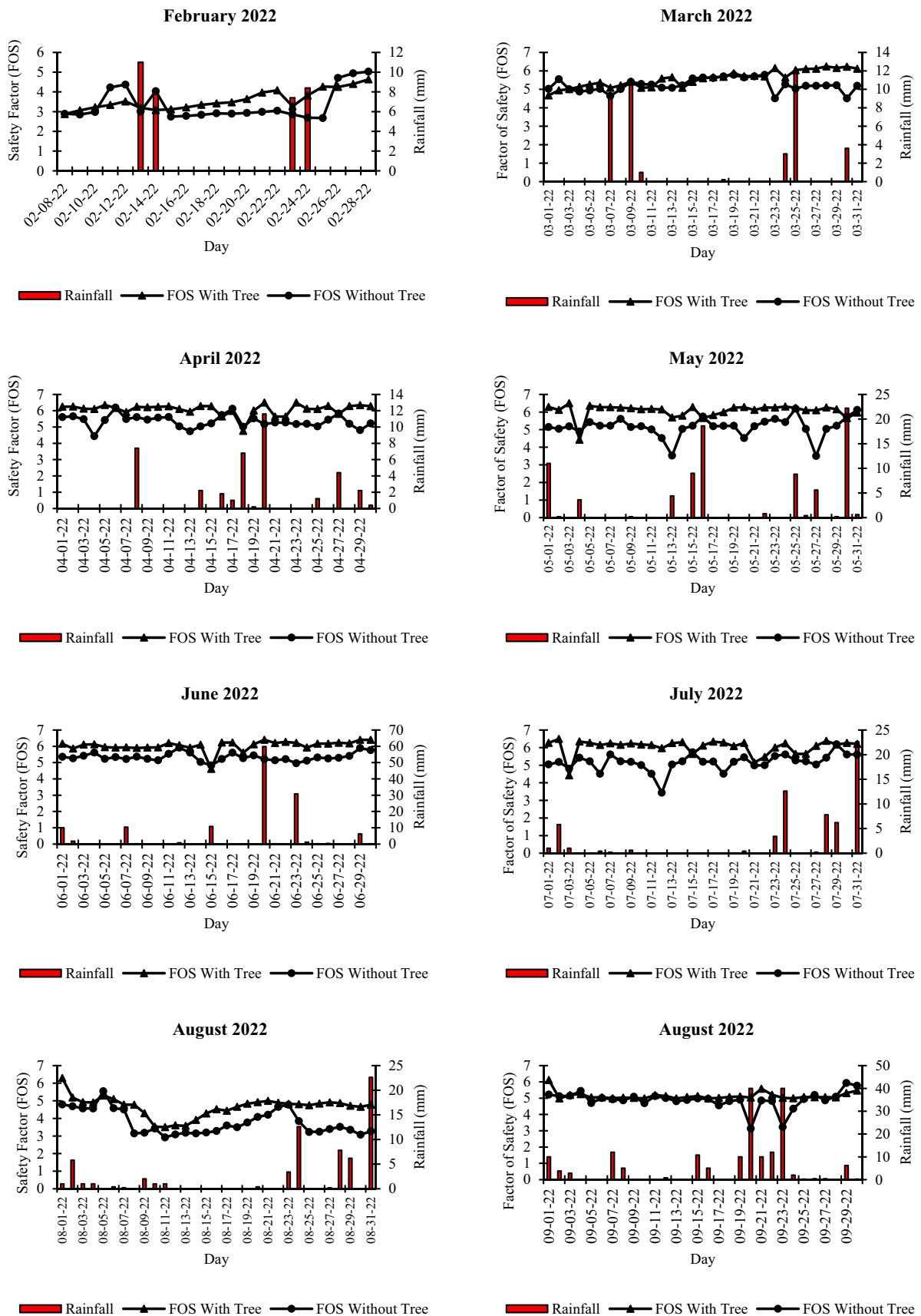


Fig. 16 FOS variations during 8 months of on-site monitoring

Table 3 LSD analysis conducted on different parameters of the study

Compared parameters	Absolute mean difference	Remarks
Rainfall precipitation against distance of tensiometers from the tree	5.84	Discrepancy is substantial at $p=0.05$, $LSD=0.04147$
Rainfall precipitation against slope depth	7.36	
Rainfall precipitation against station area	7.91	
Distance of tensiometers from the tree against slope depth	1.53	
Distance of tensiometers from the tree against station area	2.08	
Slope depth against station area	0.56	

Table 4 Pearson's correlation coefficient of the four assessed parameters

Variables	Rainfall precipitation	Distance of tensiometers from the tree	Slope depth	Station area
Rainfall precipitation	1.0			
Distance of tensiometers from the tree	8.65×10^{-16}	1.0		
Slope depth	6.94×10^{-17}	-5.1×10^{-17}	1.0	
Station area	0	0	0	1.0

absorption in the soil is observed to increase during periods of tree moisture absorption and decrease during rainfall events. The findings can be concluded as below:

- The changes in tree moisture absorption, particularly on slopes with a tree, differed from those without a tree. This study highlighted the significant influence of a vegetation on altering the distribution of tree water uptake in slopes with residual tropical soils. Throughout the study, fluctuations in climatic conditions led to variations in the profiles of tree moisture absorption. The presence of a tree at the slope crest resulted in substantial variations in matric suction profiles. In contrast, slopes without trees exhibited less pronounced variations in tree moisture absorption arrangements.
- The typical dimensions of the cutting slope and the location of the tree at the slope crest were taken into account in this study. Soil suction arrangements at specific distances and depths from the tree were depicted and integrated with the slope analysis. The contour plots of matric suction at different times demonstrated the influence of tree water uptake, particularly near the mature tree where the maximum values were observed. In summary, these findings highlight how *Alstonia Angustiloba* tree can significantly impact the removal of moisture from soil. Consequently, the investigations provided evidence of how moisture variations in unsaturated soil slopes are influenced by the transpiration process.
- Over the course of 8 months, the FOS of vegetated slope and unvegetated slope was compared. The presence of mature trees considerably increased the tree moisture absorption process. The data also showed that on slopes with trees, FOS rose by up to 53.00% (from 2.17 to 4.57). Furthermore, the effect of tree root zones was considered, which contributed to improved soil qualities and improved geotechnical slope designs. This stresses the need of community tree protection, as trees play an important role in overall slope stability.
- The presence of the *Alstonia Angustiloba* tree at the slope crest had a substantial impact on the FOS value of the soil slope. Furthermore, Pearson's correlation coefficient revealed no relationship between precipitation, space interval of the tensiometer from the tree, station area, and slope depth.

The study's findings show that the single mature tree had a significant impact on the geotechnical field which successfully stabilized the slope through tree moisture absorption. This resulted in a considerable rise in the safety factor (FOS) value, which increased from 2.17 to 4.57, a 53.00% increase.

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Authors Contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by MSIZ and MH. The first draft of the manuscript was written by MSIZ, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability All data generated or analysed during this study are included in this published article.

Declarations

Conflict of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Consent to Participate Not Applicable.

Consent to Publish Not Applicable.

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