

Influence of *Alstonia Angustiloba* Tree Water Uptake on Slope Stability: A Case Study at the Unsaturated Slope, Pahang, Malaysia

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Abstract

This study examines the effects of tree water uptake at different depths and distances on the improvement of induced water uptakes in soil owing to transpiration. This study is performed to examine the tree water uptake profile in a vegetated slope with the existence of *Alstonia Angustiloba* mature tree at the top and the permanence of the slope during various precipitation penetration events by which the data of the tree water uptake produced within this section of the slope is recorded and implemented to evaluate the factor of safety (FOS). Slope stability analysis is further conducted to explore how plant transpiration affects slope stability. The results portrayed that, higher tree water uptake lead to the greatest FOS of the slope up to 53% (from 2.17 to 4.57). The highest tree water uptake recorded was at the slope station with the existence of the *Alstonia Angustiloba* tree with a depth of 0.25 m and a distance of 1.1 m from the tree. The tree water uptake utilized in this study can contribute to a carbon-free and eco-friendly approach which can be implemented globally to prevent slope catastrophe.

1. Introduction

In most nations around the globe, residual soil exists commonly in equatorial locations, where frequent precipitation and mild climate are beneficial to erosion, which culminates in profound residual soil profiles (Schiavon et. al., 2019; Zaini et. al., 2020a). Mineralogical composition and microstructure (Hasan et. al., 2021; Zaini et. al., 2022a) are the two key factors that might contribute to the distinctive properties of residuals. In this type of soil, geological disasters such as landslides are highly to occur. Avalanche is one of the greatest catastrophic geological disasters found in steep places, that has drawn significant interest in geological and geotechnical engineering investigations (Goh et. al., 2020; Zaini et. al., 2020b) due to the considerable economic repercussions (Zhang et. al., 2022). Landslide encompasses exterior and downward motions of slope particle formation owing to attraction stress via a range of movements such as collapsing, slipping, running and any amalgamation of the above (Pradhan & Siddique, 2020).

Recurrent slope collapse along biological and constructed slopes is of relevance as it endangers lives, inhibits economic development, and degenerates the environment (Awang et. al., 2021; Chen et. al., 2013). Regional populations, visitors and pilgrims are under continuous risk of different environmental disasters, for instance, seismic activity, avalanches, overflows, deluges, and forest fires (Pradhan & Siddique, 2020). In both the geological engineering profession and academia, the topic of slope stability has been a focus of inquiry for the last seventy years. Numerous approaches suggested in compliance with the existing computational techniques have been refined to attain maturity and acquired the support of the engineering field (Zolkepli et. al., 2021; Bouzid, 2022). No universally agreed explanation of the factor of safety (FOS) subsists. For most bearing capacity problems, the FOS is commonly determined on the premise of the maximum load-bearing capacity. However, for slope stability calculations, it is more convenient that the FOS is connected to the typical strength characteristics of the soil (Oberhollenzer et. al., 2018).

Slope stability difficulties draw substantial attention from scientists around the globe, and thus, numerous strategies and approaches for slope stability evaluation have been developed (Ishak & Zaini, 2018; Basahel & Mitri, 2017). Slope stability alludes to the state of slanted soil slopes to resist motion, which has noteworthy impacts on the protection of structures, for instance, streets, levees, railroads, open unearthing, and dumpsites (Zaini et. al., 2019; Bastola et. al., 2020; Zaini et. al., 2022b). A slope catastrophe can be affected by a few components, acting jointly or solitary, counting water penetration (Zolkepli et. al., 2018; Ishak et. al., 2021a; Ishak et. al., 2021b), snow dissolving, icy masses dissolving, rising of groundwater (Ishak et. al., 2018b), chemical and physical weathering of soils, and earth quaking triggered by neither seismic tremors nor anthropoid exercises (Zolkepli et. al., 2019; Wang et. al., 2021). In reality, numerous slope catastrophes were examined after failure. The stabilization of slope evaluation is formidable since the slope catastrophe can be ascribed to various components as specified above and the complication to find the foremost plausible slip surface within normal situations (Kardani et. al., 2021). Thus, there are a lot of approaches to stabilizing the slope which include the utilization of vegetation via the tree water uptake method.

Verdure is contemplated useful to slope stability not only through mechanized soil fortification (Zhu and Zhang, 2019) but also through root water uptake (Zhu et. al., 2018). Throughout the uptaking manner, plant roots assimilate dampness via chemical change and expiration (Rees et. al., 2012), which, resulted in desiccating the soil encompassing the plant roots (Rees et. al., 2006) and consequently actuating soil suction (Zhu & Zhang, 2015; Feng et. al., 2020). The fortification impact of plant roots has been well acknowledged around the world, whereas root-water uptake has not however been completely examined (Ni et. al., 2018; Liang et. al., 2020). Root-water uptake is a vital component that significantly influences the temporal-spatial water substance conveyance in shallow verdure soil (Nyambayo and Potts, 2010; Ai et. al., 2020). Nevertheless, this process and its intelligence with soil are not so much realized owing to the inalienable changeability of root engineering and inherent challenges of perceiving below-ground stream forms (Woodman et. al., 2020; Zaini et. al., 202a). As examined by Ishak et al. (2021a) soil states (e.g. water powered conductivity and entrance resistance), and sorts of verdure (e.g. root dissemination).

Recently, broad exploratory ponders have been investigated to measure intake enticed by distinctive verdure species amid the evaporation and transpiration process. The universality of root geomorphology is fundamental for evaluating the hydrodynamic execution of stagnated frameworks. In addition, recognizable proof of the pattern of root geomorphology that improves soil water intake viably attracts specific consideration. Thus, this study aimed to investigate and monitor the soil water intake dispensation owing to the tree induced suctions created at the top of the soil slope. The modifications of the soil water intake were analyzed to gain the soil moisture profiles near the tree. In addition, we hypothesized that: 1) soil matric suction of the *Alstonia Angustiloba* tree may contribute to enhancing the stability of the tropical residual slope; 2) the moisture variation or the matric suction has been altered via transpiration process in a tropical residual soil slope, and; 3) the tree induced suction may affect the Factor of Safety (FOS) projected to different weather conditions. Thereby, the goals of the current study were to 1) ascertain soil matric suction at a slope with a mature tree existing at the top of the slope, 2)

establish a soil water intake contour dispensation at the active root zone of the tree and; 3) analyze the effect of tree induced suction on Factor of Safety (FOS) at the chosen slope.

2. Experimental Design And Measurements

2.1 Description of Study Site

Figure 1 illustrated the location of the study conducted. As illustrated in the figure, the tropical residual soil slope with the existing *Alstonia Angustiloba* mature tree is situated in Pahang, Malaysia (3° 48' 45.36"N, 103° 19' 32.16"E). The tropical residual slope studied is uniform and appears to be a cut slope. The area of the slope was about 15 m wide (measured across the slope) and 3 m height (measured down to the slope) with a single mature tree (*Alstonia Angustiloba*) which was located at the top of the slope with the tree height reaching up to 11 m. There are a total of thirty (30) tensiometers installed in the study area with thirty (3) gypsum blocks to measure the suction of the tree.

2.2 Determination of Physical Properties of the Tropical Residual Soil

There are three (3) physical properties investigated in this study which comprise particle size distribution, Atterberg limit, and specific gravity. The particle size distribution for fine-graded soil passing sieve size 63 µm was performed according to BS 1377: Part 2: 1990: 9 for sieve analysis and ASTM D 422: 1998 for hydrometer analysis. The grain size distribution of fine soil, especially for particles that is finer than 63 µm was determined by conducting the hydrometer test. In this study, the sieves used for particle sizes of tropical residual soil were 20 mm, 10 mm, 4.75 mm, 2.36 mm, 1.18 mm, 0.6 mm, 0.3 mm, 0.15mm, and 0.063 mm. The results of percentage passing versus sieve or particle size were plotted in the semi-logarithmic graph.

The plasticity ranges of clay soil can be measured in numerical expression by using Atterberg limits since the moisture content in clay soils was also known as plastic consistency. The test of tropical residual soil was conducted by using the test method since the size range of their particles was finer than 63 µm. The tropical residual soil tends to appear in four (4) states depending on certain moisture content, which is solid, semi-solid, plastic, and liquid. By using the cone penetration or the cone penetrometer method, the liquid limit test was conducted according to BS 1377: Part 2: 1990: Clause 4.3, while the plastic limit was conducted according to BS 1377: Part 2: 1990: Clause 5.3. The term plasticity index (BS 1377: Part 2: 1990: Clause 5.4) comes from the mathematical variation between the liquid limit and plastic limit.

The specific gravity of tropical residual soil was examined by carrying out the small pycnometer test by referring to BS 1377: Part 2: 1990:8. The soil samples were put inside the small pycnometer, where the distilled water was already filled half of the pycnometer which were then placed inside a vacuum chamber for 24 hours. The air that existed in the sample that contained the distilled water and the mixture of the material was removed by the vacuum chamber. Then, the mass of the pycnometer was measured afterwards. The specific gravity is calculated by using Eq. 1.

$$G_s = \frac{m_2 - m_1}{(m_4 - m_1) - (m_3 - m_2)}$$

1

Where m_1 is the mass of the empty pycnometer, m_2 is the mass of the pycnometer with dry soil, m_3 is the mass of the pycnometer with soil and water, m_4 is the mass of the pycnometer and water and G_s is the specific gravity. The experimental setup for the physical properties of tropical residual soil is shown in Fig. 2(a).

2.3 Determination of Shear Strength of the Tropical Residual Soil

The calculation of bulk and dry density (ρ_b & ρ_d) and moisture content (ω) of the soil sample was performed before Consolidation Isotropic Undrained (CIU) test. The test was conducted based on the techniques described in BS 1377: Part 4: 1990: 3.4 to acquire the correlation between moisture content with dry density. Figure 2(b) demonstrates the experimental setup in determining the shear strength of the tropical residual soil.

Three (3) soil samples (38 mm diameter with 76 mm height) using a simple soil splitter were prepared to perform the Consolidated Isotropic Undrained (CIU) triaxial compression test as shown in Fig. 2(b). Various confining pressures of 100 kPa, 150 kPa, and 200 kPa to determine both saturated (c' , φ') and unsaturated (φ^b) shear strength parameters via GDS Fully Automated Triaxial System (GDSTAS) were conducted. The CIU triaxial compression test was conducted in order to acquire the shear strength under different confining pressure for the tropical residual soil. Based on Ishak et. al., (2021a), in Malaysia, the CIU test is more suitable for examining the shear strength parameters of the soil owing to most of the soil being in consolidated and undrained condition. The CIU triaxial compression test was performed according to BS 1377: Part 8: 1990:7

2.4 Field Monitoring Work

The tensiometers and gypsum moisture block are used to evaluate the water uptake in soil which is less than 100 kPa and more than 100 kPa respectively. A combination of tensiometers and gypsum moisture blocks was utilized to evaluate the tree water uptake in exploration to view the considerable matric suction induced by the transpiration process. The good reliability and capability of instruments are vital to represent exploration data for further simulation and analysis of condition slopes. In this study, six (6) stations of tensiometers and gypsum moisture blocks were placed at the slope area and at the flat area, namely as Slope Area 1 (SA 1), Slope Area 2 (SA 2) and Slope Area 3 (SA 3) together with Flat Area 1 (FA 1), Flat Area 2 (FA 2) and Flat Area 3 (FA 3) as shown in Fig. 1. Each station consists of a top, middle and bottom of the root zone to monitor the profile of the matric suction changes in both areas (Ishak et. al., 2021b). According to Zaini et. al., (2020a), each station of tensiometers was located at a distance of 1.1 m (0.1h), 2.2 m (0.2h) and 4.4 m (0.4h) from the tree. The distance of the tensiometers was set based on the height of the tree ($h = 11.0$ m). Therefore, the distance from the tree for each area (Slope Area and Flat

Area) were 1.1 m, 2.2 m and 4.4 m from the tree trunk and were embedded vertically in the soil down to the depth of 0.25 m, 0.5 m, 1.0 m, 1.5 m and 2.0 m as shown in Fig. 3. The gypsum blocks and tensiometer were set-ups with the same arrangement for this field monitoring. The performance and calibration testing were carried out in ensuring the reliability and capability of the instrument (tensiometer and gypsum moisture block) in a low and high matric suction by utilizing the same depth (0.25 m) and distance (0.5 m) between the tensiometers and gypsum moisture blocks of different stations. Figure 4 shows the calibration curve of the tensiometer and gypsum moisture block. The accuracy of the tensiometer is higher than the gypsum moisture blocks which range from 10 kPa to 80 kPa (see Fig. 4).

The gypsum block (Delmhorst Instrument Co. Model 5KS-D1 G-Block) was utilized owing to measure the higher range of suction which is beyond 100 kPa up to 1000 kPa. A total of thirty (30) units of the instruments were installed at different depths which were at 0.25 m, 0.5 m, 1.0 m, 1.5 m and 2.0 m at the vicinity of the trees at the top of the slope as shown in Fig. 3 to measure the in-situ soil matric suction. Each station (FA 1, FA 2, FA3, SA 1, SA 2 and SA 3) was installed with five (5) gypsum blocks considered as the top, middle and bottom of the root zone according to Biddle (2001) and the active root zone were assumed has extended until to a depth of 2.0 m. The gypsum block soil moisture measuring system consists of two (2) parts which are the gypsum soil block (sensor) and the measuring instrument Moisture Tester (see Fig. 3). The gypsum block was connected by lead wires into two (2) springs loaded binding posts on the meter reader. The data were observed through soil moisture tension and electric resistance to record the matric suction value. This procedure can be conducted after the gypsum block was soaked in water for at least one (1) hour and the calibration button was set to determine the initial reading for saturated condition and were allowed to dry.

A tensiometer consists of a sealing cap, a tube with a porous ceramic tip at the bottom and a vacuum gauge near the top. When the soil desiccated and the water flows out from the tensiometer, it produce a vacuum inside the tensiometer that was shown on the gauge. As the vacuum produced is equivalent to the tree water uptake, water will stop moving out from the tensiometer. The Jet-fill Tensiometer Model 2725 with a total number of thirty (30) units were installed at different depths which were at 0.25 m, 0.5 m, 1.0 m, 1.5 m and 2.0 m to measure the in-situ soil matric suction. Biddle (2001) and Rees & Ali (2012) measured the moisture content and changes of moisture content in the tree proximity by using a neutron probe and found that the influence of the plant root was intensively related to the depth of not more than 2.0 m. Hence, it is assumed that the set-up tensiometers at the greatest deepness of 2.0 m should be adequate to allow a good evaluation of the alterations in tree water uptake in the study area.

At the corner of about 20 m from the tree in the study area, tripod staph was placed in order to obtain accurate readings without the influences or interception of the tree. The bucket of rain gauge was placed on tripod staph to give a plane base for rain gauge set-up, as the tipping bucket of the rain gauge must be set up at the flat surface to provide a precise measurement. The model of Rainew (see Fig. 3) with a current counter-logging rain gauge with a tipping bucket was set up at the study area to evaluate the continuous real-time precipitation rate. The tipping bucket rain gauge was readily connected to the Rain Log 2.0 event data logger of 16 MB non-volatile data storage. In most cases, 8000 data points that are

similar to the accumulative total precipitation amount of 1600 mm can be logged. A cable to the tipping bucket inside the rain gauge was connected to the hydrologger and was located at the toe of the slope with a time interval of 15 minutes. During rainfall occurrence, the bucket tips will record the total number encountered within each interval and store in the hydrologger. The rainfall data will be downloaded once per month for six (6) months. In order to guarantee that the rain gauge was working correctly, the calibrated procedure was applied during this period of logging. Moreover, for the data recording, the calibration was conducted by stationing a container loaded with 373 ml of water at the top of the rain gauge. The water was permitted to flow through a small pre-drilled aperture at the base of the container. Moreover, the field monitoring works was conducted for eight (8) months starting from February 2022 to September 2022

2.5 Determination of Soil Suction Contour at the Active Root Zone

The 2-Dimensional and 3-Dimensional soil matric suction contour was developed via GiD software and Surfer software respectively using the definition of materials, geometry, parameter, solution information and conditions. The software generates a mesh for finite elements and generates details of a mathematical simulation of the typical geometrical slope of the study area. Hence, the field monitoring data monitored for six (6) months were applied in this software and was presented to visualize the results and analysis of the tree water uptake.

2.6 Assessing the Slope Stability of the Unsaturated Tropical Residual Soil Slope

To reveal the performance of the slope stability, each related input data must be provided to implement the approached equation. Since this study involved the slope stability with adverse pore water pressure whereas the tree water uptake, some steps in assessing the stability of the slope analysis were implemented (Fredlund and Rahardjo, 1993); 1) the slope geometry survey with a proper investigation on the selected slope surface; 2) detail investigation in identifying stratigraphy of rock/soil and acquired the undisturbed soil specimens; 3) obtain suitable parameters (c' , ϕ' and ϕ^b) particularly shear strength for each material (soil/rock) stratigraphy through laboratory testing; and, 4) The measurement of adverse pore water pressure (matric suction) above the groundwater table. The consideration in absence of the mature tree at the top of the slope was considered via performing a fully saturated slope whereas $u_a - u_w = 0$ and $\phi^b = 0$.

Through the commercial software of SLOPE/W version 7.03, 2007, the initial basic checks of the slope stability results were generated and compared to the previous approach equation. Besides, the critical slip surface found by trial and error was also determined using the SLOPE/W software. There are 64 possible failure surfaces that were examined to find the critical slip surface as demonstrated in Fig. 5. In the study, to evaluate the weight of the soil bounded utilized to Eq. 2, the critical slip surface was separated into

fifteen (15) slices. The real slope arithmetic completed with the critical slip surface moved through the top of the slope, the position of each slice and slope elevation were shown in Fig. 5.

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

2

Where, c' is the cohesion, l is the slip arc length, R is the radius of circular failure surface (m), W is the surcharge load (kN), β is the angle between the tangent to the centre of the base of each slice and the horizontal, ϕ' is the internal friction angle of the saturated soil and ϕ^b is the internal friction angle of the unsaturated soil. The lowest FOS of 1.868 was evaluated by using SLOPE/W software through the traditional method of slices. To examine the differences and percentage differences of FOS with other selected methods, the FOS of 1.868 was utilized as a referenced value. This specific slip surface coincides with a radius of 3.88 m and origin $x = 5.00$ m, $y = 7.88$ m from the marked point at the studied tropical residual soil slope. The result acquired for this specific slip surface were implemented from Eq. 2 in contrast to the multiple approaches accessible in SLOPE/W software. Figure 5 shows the variations between various approaches ranging from 1–4% in contrast to the manual evaluation. The difference between the Eq. 2 and the Ordinary method (Fellenius Method- SLOPE/W) usage was small owing to the fact that these two (2) methods were adopted from a very similar formula in approach and equation.

2.7 Statistical Analysis

Numerical interpretations were performed using Microsoft Excel 2010. One-way Analysis of variance (ANOVA) was conducted to collate the rainfall intensity and the soil matric suction. Fisher's least significant difference (LSD) was used to identify significant differences between means separation at a level of $p < 0.05$. Furthermore, Pearson's correlation analysis was used to determine the correlations between the rainfall intensity, distance of tensiometers from the tree, depth of the slope and station area. The error bars were used to indicate whether the results obtained are significantly different as discussed in detail in section 3.6.

3. Results And Discussion

3.1 Physical Properties of Tropical Residual Soil

The main physical property performed in this study comprises sieve analysis, Atterberg limits, and specific gravity. According to the British Soil Classification System (BSCS), the tropical residual soil was categorized as having very high plasticity of sandy SILT (MVS) soil. The result of sieve analysis from a portion of 100g soil specimen comprises 4.2% greater than 2 mm (gravel), 27.9% within the size of 2 mm to 0.063 mm (sand), 45.1% within 0.063 mm to 0.002 mm (silt), and 22.8% is lower than 0.002 mm (clay). Figure 6 demonstrates the PSD of the tropical residual soil for the unsaturated slope studied. Besides, the Atterberg Limit of tropical residual soils from the study area suggested that the liquid limit (LL) of the soil was 70.0%, the plastic limit (PL) was 31.0% and the Plasticity Index, (PI) was 39.0%. According to the

British Soil Classification System (BSCS), the soil at the site study at the field can be categorized as SILT of high plasticity (MHS) with a relative density of 2.74. As stated by Zaini et. al., (2020a), owing to a wide modification of metallurgy, the relative density of tropical residual soils is commonly low or uncommonly high. The physical properties values obtained in this study are coherent with the investigation performed by Ishak et. al., (2021a) and Zolkepli et. al., (2018).

3.2 Unsaturated Shear Strength of Tropical Residual Soil

As reported by Ishak et. al., (2021b), the latest criterion presented was the unsaturated friction angle, φ^b which is always smaller than or equivalent to the saturated friction angle, φ' . Rees & Ali (2012) deduced the shear strength of soil is rectilinearly proportionate to the tree water uptake (where $\varphi^b = \varphi'$), where the tree water uptake is smaller than the air-entry value. Table 1 shows the experimental shear strength values of unsaturated soil friction angle, φ^b at multiple places in Peninsular Malaysia including the studied unsaturated friction angle, φ^b of the tropical residual soil. Based on Table 1, the unsaturated friction angle, φ^b was assumed lower than or equivalent to the saturated friction angle, φ' (Rahardjo et. al., 2004; Huat et. al., 2005; Zolkepli et. al., 2018; Zaini et. al., 2020a; and Ishak et. al., 2021a).

Table 1
Experimental values of unsaturated friction angle, φ^b of
the tropical residual soil at various locations in
Peninsular Malaysia

Researcher	Location	φ' (°)	φ^b (°)
Author	Pahang	25	21
Ishak et.al. (2021a)	UTM	23	20
Zaini et. al., (2020a)			
Zolkepli et.al. (2018)	Pahang	25	17
Huat et.al. (2005)	Selangor	26	26
Rahardjo et.al. (2004)	Singapore	25.1	24.3

An investigation performed by Fredlund et.al (1996) explained that the value of the unsaturated friction angle, φ^b is lower or equivalent to the saturated friction angle, φ' at a lower or high value of tree water uptake, the value of the unsaturated friction angle, φ^b will decrease to a lower value. More water will expel out from the pores of the soil with no further increase of net stress when the matric suction increases (Ishak et. al., 2021a). Figure 7 illustrates the Mohr's Circle and the effective stress failure envelope for samples 1, 2 and 3. Based on Fig. 7, the effective friction angle (φ) and the effective cohesion (c') are 25° and 9 kPa respectively.

3.3 Effects of Single Respond Event to the Soil Suction Distribution Pattern of the Tropical Residual Soil Slope

3.3.1 Effects of Intense Rainfall on the Soil Suction Distribution Pattern of the Tropical Residual Soil Slope

Researchers such as Lim et.al. (1996), Gasmo et.al. (1999), Gofar et.al. (2008) and Kassim (2011) investigated the response of tree water uptake dispensation owing to a single rainfall pattern on the slope with further diminishing the secular period in the examination. The central to their investigation was insulating precipitation patterns during observation time intervals as multiple precipitation patterns were signified by intense precipitation and prolonged precipitation. Coherent to that, the tree water uptake dispensation patterns for the tropical residual slope without the existing mature tree and with the existing *Alstonia Angustiloba* mature tree were displayed as per findings performed by the previous researcher with a further comparison of the slope with and without a tree at the top of the slope. The explanation of the precipitation pattern of intense rainfall occurred subsequent to a prolonged dry period. From February 2022 to March 2022, the slope without trees faced the driest states throughout the site observation period which was without any rainfall for ten (10) days. The highest suction recorded at the depth of 0.25 m, 0.5 m, 1.0 m, 1.5 m and 2.0 m were 60 kPa, 62 kPa, 62 kPa, 64 kPa and 66 kPa respectively. These results show that the greatest tree water uptake value by the tropical residual soil is 66 kPa, even during the protracted dry period. However, a normal intense and short tropical precipitation that took place on 24th February 2022 induced the tree water uptake at 0.25 m to 2.0 m depth to dramatically fall to the lowest value as demonstrated in Fig. 8.

Figure 8(a) shows the plotted of mean tree water uptake with profiles at slope without tree, demonstrating that substantial tree water uptake can establish during protracted desiccated time intervals even though the tree water uptake has been immediately dissipated with the occurrence of short and intense precipitation events. However, the worst pore-water pressure states did not reach positive pressures at all deepness. The mean tree water uptake profile with depth at slope without tree highlighted that substantial tree water uptake has been readily dissipated with the events of the precipitation with a value of 8.4 mm on 24th February 2022. The suction pattern at 0.25 m, 0.5 m, 1.5 m and 2.0 m depth dropped to the minimum value of 14 kPa, 18 kPa, 26 kPa, 36 kPa and 45 kPa respectively. For a prolonged dry period with sudden intense rainfall events continuously for about ten (10) days without any precipitation, the greatest tree water uptake was observed at the top of the unsaturated slope with the presence of *Alstonia Angustiloba* tree at a depth of 0.25 m, 0.5 m, 1.0 m, 1.5m and 2.0 m were 110 kPa, 96 kPa, 90 kPa, 84 kPa and 66 kPa respectively. The results show that the greatest tree water uptake value of the soil is 110 kPa. The mechanism of high matric suction was identical to the matric suction condition recorded during the prolonged dry period which will be discussed later. Eventually, pursued by the intense precipitation event, the tree water uptake fell but did not achieve the lowest value of tree water uptake at the slope without a tree.

The tree water uptake at the deepness of 0.25 m and 0.5 m dropped from 110 kPa to 84 kPa and from 96 kPa to 80 kPa respectively, while it dropped uniformly at the depth of 1.0 m from 90 kPa to 88 kPa. Subsequently, the matric suction at 1.5 m and 2.0 m depth dropped to a small value only which were

from 84 kPa to 79 kPa and from 66 kPa to 60 kPa respectively. The suction at depths 0.25 m and 0.5 m were delicate to intense precipitation events compared to the depth of 1.0 m, 1.5 m and 2.0 m which were not greatly affected. Although both of the slopes obtained an equal quantity of precipitation but the variation responses in tree water uptake value can be certainly demonstrated at a slope with a tree at the top (See Fig. 8 (b)).

3.3.2 Effects of Antecedent Rainfall on the Soil Suction Distribution Pattern of the Tropical Residual Soil Slope

The tree water uptake demonstrated periodic variation during desiccated time intervals mainly due to the periodic variation in solar emission during day and night. The result insinuates that other than the precipitation penetration, the earth's surface surrounding such as the breeze, climate, dampness and solar emission could alter the tree water uptake as well. When both of the slopes received moderate rainfall on 18th April 2022, the suctions at 0.25 m down to 1.5 m dropped gradually while the suction at 2.0 m dropped not as greatly as other depths. Figure 9(a) and 9(b) show the tree water uptake profiles on the tropical residual slope with and without trees as a result of antecedent precipitation. The tree water uptake at 2.0 m was only altered by the intense rainfall that occurred on 20th April 2022. The results suggested that the arrangement of the rainfall act as a crucial parameter in the propagation of infiltration of water on both slopes. Both profiles also revealed that the continuous low intensity of rainfall that occurred from 17th April 2022 to 18th April 2022 has no significant effect in reducing the matric suction. In the period of the antecedent rainfall pattern, the lowest suctions were encountered at 0.25 m, 0.5 m and 1.0 m on 19th April 2022. Nonetheless, the antecedent rainfall from 18th April 2022 to 19th April 2022 on both slopes shows significant effects on the distribution of the suction.

Additionally, the comparison of the rainfall pattern illustrated in Fig. 9 shows a good agreement of suction distribution pattern in the period of rainfall pattern in both slopes has been achieved. It can be summarized that a canopy interposing was trivial owing to the moderately and antecedent intense quantity of precipitation that occurred and there was no significant difference in terms of the tree water uptake between the slope with a tree at the top and the slope without a tree (Hongde et. al., 2021).

3.3.3 Effects of Prolonged Antecedent Rainfall on the Soil Suction Distribution Pattern of the Tropical Residual Soil Slope

In the period of continuous daily rainfall from 20th June 2022 to 26th June 2022 for both of the slopes, owing to the greater precipitations, the tree water uptake was substantially diminished as demonstrated in Figs. 10(a) and 10(b). Based on the amalgamation of intense and antecedent precipitation, the lowest tree water uptake at 0.25 m, 0.5 m and 1.0 m were encountered on 23rd June 2022 due to the highest rainfall amount on 20th June 2022 (60 mm/day). From the results, it can be summarized that the lowest tree water uptake in the soil in both of the tropical residual soil slopes in the study area was controlled by the precipitation intensity jointly with the antecedent precipitation. At all depths, the worst pore-water pressure did not reach the saturated state which was at 0 kPa value. Therefore, the canopy interposing

was trivial owing to the event of moderately and antecedent intense quantity of precipitation which allowed rainfall to blow on the soil under the canopy of the tree (*Alstonia Angustiloba*).

During the wet period which was at prolonged and antecedent rainfall, the matric suction decreased due to the high precipitate of water in the soil. At this condition, the results show no substantial variations between matric suction within the proximity of the tree and without the tree at the slope. During the no rainfall period, the matric suction on the slope without a tree increased slower compared to the slope with a tree at the top. Moreover, the preserved mature tree (*Alstonia Angustiloba*) would expedite the tree water uptake and serve as an effective method to reduce soil moisture. During the dry period, the matric suction within the vicinity of the tree was remarkably higher than the tree water uptake subjected to the distance of the mature tree. The dry soil with high matric suction would lead to an increment of soil strength within the proximity of the mature tree.

3.3.4 Effects of Prolonged Dry Condition on the Soil Suction Distribution Pattern of the Tropical Residual Soil Slope at Different Stations

The response of suction distribution of various rainfall patterns during eight (8) months of field monitoring at the study area shows that the soil lost its moisture intake regularly after undergoing normal minor and major precipitation events. The intense and short precipitation and precipitation amount tend to be one of the leading factors to the water intake alteration at a slope without a tree but not at a slope with a tree at the top. The tree canopy can be a component to effect the tree water uptake alteration at the slope with the tree as the canopy interposing will diminish the amount of precipitation infiltration into the soil. The antecedent and prolonged rainfall were identified as the major dominant factor to a suction variation on both of the slopes (with and without trees) in the study area. In the period of this field monitoring, a period without rainfall was encountered from 13th February 2022 to 22nd February 2022. These conditions were recorded to represent the tree water uptake profile at all locations which were at SA 1, SA 2, SA 3, FA 1, FA 2 and FA 3. Coherently, the tree water uptake profiles right after the antecedent and prolonged precipitation on both slopes which were at slope without a tree and slope with a tree at the top were recorded as presented in Figs. 11(a) and 11(b). The data collected on 13th February 2022 was identified as the lowest matric suction value which was determined as the initial condition.

Figures 12(a) and 12(b) show the results on 18th February 2020 of the continuing increment value of matric suction after ten (10) days without rainfall. Due to the exposure to the dry period, the tree water uptake at the top of 2.0 m depth has greatly increased. In addition, the highest matric suction was encountered at SA 1 and FA 1 at the deepness of 0.25 m and 0.5 m respectively with a value of 66 kPa, 56 kPa; and 56 kPa, 48 kPa respectively compared to the slope without a tree.

The data collected on 22nd February 2022 illustrates in Figs. 13(a) and 13(b) show the maximum value of the tree water uptake during the desiccated condition. The changes in tree water uptake dispensation arrangements were produced in various states. After ten (10) days without rainfall, the tree water uptake at the top of 2.0 m increases constantly to the right. Besides, the tree water uptake at 1.1 m from the *Alstonia Angustiloba* mature tree at SA 1 and FA 1, particularly at the deepness of 0.25 m and 0.5 m were

higher than at slope without the *Alstonia Angustiloba* mature tree with a matric suction of 110 kPa and 96 kPa (SA 1) and 90 kPa and 88 kPa respectively (FA 1).

The comparison of the matric suction between the slope with a tree at the top and the slope without a tree was done by the previous researcher such as Zhu & Zhang (2015) and Feng et.al. (2021). Based on the investigation performed by the previous researchers, the tree water uptake created in bare and vegetated soil columns in the site and physical prototype in the soil laboratory yielded a result that proved 100% of tree water uptake produced in the stagnated pillar was greater than the barren soil pillars. Coherent to that, the evaluated tree water uptake at the slope without a tree was ascribed to the evaporation process which was lowered than at the slope with a tree at the top as it was engendered by the transpiration process. As clearly shown in Figs. 13(a) and 13(b), the dispensation of the tree water uptake at 1.1 m from tree was significantly greater than the tree water uptake at 4.4 m from the tree and with the slope without a tree. The comparison of the matric suction distribution at SA and FA for both 13th February 2022 and 22nd February 2022 demonstrates that the tree water uptake at SA was higher than FA owing to the growth of active roots in a lateral position that the underneath growth with better focused at SA (Ishak et. al, 2021b).

3.4 Representation of Field Monitoring at the Tropical Residual Soil Slope Corresponding to the Various Rainfall Events

The model of slope illustrated in Fig. 14 consists of 86 elements of quadrilateral mesh with 90 nodes for the 2D model generated using GiD software and 120 nodes for the 3D model using Surfer software. The matric suction was presented according to the mesh and nodes in revealing a typical drying pattern or soil moisture deficit which was considered as moisture migration effected by a single mature tree at the top of the slope. By assuming the root region to an extent of 2.0 m depth and a radiated distance of 4.4 m symmetrical for both right and left from the focal point of the tree. The consideration of the root region extends laterally and beneath the top of the slope. Hence, some drying patterns with high matric suction from the top of the tree to the slope crest can be expected from this situation. At 0.25 m and 0.5 m depth of antecedent rainfall, the lowest water uptake recorded were 56 kPa and 60 kPa on 13th February 2022 respectively. The volume of rainfall penetration on the sloping surface was small owing to the water runoff.

The field monitoring result of 18th February 2022 showing an increment in tree water uptake produced by the tree water uptake was applied on a mesh model as shown in Fig. 14. Figure 14 also revealed that the changes of the tree water uptake modifications or soil moisture loss proximity of the mature tree within the slope have occurred. The figure also showed the presence of the greatest suction of 80 kPa produced at the bottom of the *Alstonia Angustiloba* mature tree at the top of the unsaturated slope in the soil matric suction contour. Figure 15 shows the tree water uptake on 22nd February 2022 which indicated a rapidly developed tree water uptake compared to 18th February 2022. The greatest water uptake value of 110 kPa was greatest at the bottom of the tree at the top of the slope with the lowest water uptake value of 64 kPa. The absence of rainfall for ten (10) days has developed the soil suction contour which obviously indicated that the matric suction of the observed slope decreased with the increment of

distance from the tree. After several days of the antecedent rainfall event, the soil matric suction remarkably decreased owing to the high amount of rainfall infiltration. From the cycle, the soil matric suction shows a significant increase owing to tree water uptake during the dry period. It can be summarized that the existence of the *Alstonia Angustiloba* tree help to enhance the soil matric suction which increased the level of water expelled from the soil through the active root tree which is coherent with the research conducted by Hongde et. al., (2021).

3.5 Effects of Soil Matric Suction on the Stabilization of the Tropical Residual Soil Slope

As highlighted in the previous chapter, ϕ^b angle was one of the parameters that differ with the tree water uptake increment. This parameter is significantly important to influence the overall calculation of the FOS for the slope as shown in Table 2. From Table 2, it can be analysed that the magnitude of ϕ^b angle varies with the matric suction increment. As an example, for soil matric suction from saturated condition range to residual water content matric suction (0–80 kPa), $\phi^b = 20^\circ$, at residual water content matric suction (80–100 kPa) $\phi^b = 14^\circ$ and beyond residual water content matric suction (> 100 kPa) $\phi^b = 10^\circ$. Based on the remaining moisture content of matric suction, the soil shear strength envelope shows a constant value beyond the residual water content of matric suction. Figure 16(a) shows how the FOS responds to various matric suction for the values of the ϕ^b angle. The increment of FOS was due to the value of matric suction and ϕ^b angle increased with almost the same pattern as non-linear variation as indicated in Fig. 16(a). The FOS was performed using a matric suction profile which corresponds to the maximum value encountered from the field monitoring program and the calculations of the FOS were performed by using the range of the actual value of matric suction obtained from the field monitoring.

Table 2
Non-linear value of ϕ^b angle at several suction ranges

Soil Type	γ , (kN/m ³)	At suction 0–80 kPa	At suction 80–100 kPa	At suction 100–300 kPa
		ϕ^b , (°)	ϕ^b , (°)	ϕ^b , (°)
Sandy SILT	19	20	14	10

In assessing the actual slope stability in the study area, the matric suction profiles that were presented in the previous section are discussed in this section. The tree water uptake profiles encountered from the site observation work were implemented for FOS calculations. The location of the critical slip surface with slices that were integrated directly with the soil matric suction coherent to the 2D contour plot was illustrated (see Fig. 16(b)). The effect of the transpiration process from a tropical mature tree in order to induce the soil matric suction in the vicinity of the tree was used to perform the slope stability analysis

through eight (8) months of field monitoring. The field data provided useful information on the soil matric suction changes generated by the drying process of the tropical mature tree at the base of each slice.

Figure 17 demonstrates the modifications in values of the FOS against catastrophe during eight (8) months of site observations which included the combination of rainfall precipitation and FOS data. The relationship of FOS with the tree water uptake of the tropical residual soil from February 2022 to September 2022 was presented in Fig. 17. The primary FOS saturated slope was 1.868 which was lowered than the unsaturated slope with the nonexistence of *Alstonia Angustiloba* mature tree and the FOS differ with time and tree water uptake. The increment in FOS trending owing to several shifting upward of the line during the drying period can be clearly seen in Fig. 17. These arrangements of drying were separated in various circumstances, initiating in the month of February 2022 to March 2022, May 2022 to June 2022 and July 2022 to September 2022. Within these time intervals, soil moisture loss has taken place on the soil to sustain a high tree water uptake. As the tree water uptake abruptly dropped due to higher precipitation which reduced the FOS through the one-day infiltration process.

Moreover, the increment in FOS value will gradually increase within a time of one (1) to two (2) weeks after the heavy rain events occurred via the evaporation process as demonstrated in Fig. 17 (FOS without tree). Coherently, the protection of the tropical tree can greatly enhance the tree water uptake which will affect the stabilization of the unsaturated slope. On 19th February 2022 the FOS of the slope with the *Alstonia Angustiloba* mature tree at the top achieved up to 53% greater than the FOS of the slope without the existence of the *Alstonia Angustiloba* mature tree. The increment of the tree water uptake on the slope with the *Alstonia Angustiloba* mature tree at the top substantially enhanced the stability of the unsaturated slope compared to the slope with the absence of the *Alstonia Angustiloba* mature tree. The existence of the tropical mature tree has a great effect in accelerating the tree water uptake after the rainfall event and acts as a practical tool to eliminate water from the tropical residual soil which can directly poise the tropical residual soil slope.

3.6 Statistical Analysis and Determination of the Best Regression Model for Factor of Safety Prediction via Multiple Regression Analysis

The error bars indicate the standard error of the parameters observed in this study. The error bars were evaluated based on the overlapping bars between the data and the length of the error bars within the same and different groups (at $p < 0.05$) of studies (see Fig. 8 to Fig. 13 and Fig. 17) coherent to the investigations made by Hasan et. al., (2021) and Zaini et. al., (2022). The overlapping error bars indicate the insignificant differences between the data while the data that is not overlapped indicates the significant differences in the data. Based on Fig. 8(a), at the unsaturated slope without a tree with respect to the intense rainfall, the soil matric suction on 25th February 2022 at various depths shows significant differences with the soil matric suction on 22nd February 2022 to 24th February 2022 as the error bars at different depth is not overlapped with each other. However, there are insignificant differences between the soil matric suction on 22nd February 2022 to 24th February 2022 as the error bars overlapped with each other at the depth of 1.0 m to 2.0 m. There is a smaller difference between the soil matric suction between 22nd February 2022 to 24th February 2022 at the depth of 0.25 m and 0.50 m. At the

unsaturated slope with the existence of *Alstonia Angustiloba* mature tree, the soil matric suction on 22nd February 2022 to 25th February 2022 shows insignificant differences due to the overlapping of the error bars. However, the soil matric suction recorded at the slope with the existence of *Alstonia Angustiloba* mature tree is higher collated to the slope without a tree. Based on Figs. 9(a) and 9(b), both of the unsaturated slope with or without the existence of *Alstonia Angustiloba* mature tree coherent to the antecedent rainfall event shows insignificant differences in soil matric suction on 16th April 2022 to 20th April 2022 as the error bars do not overlap with each other. However, the soil matric suction value recorded for the slope without the tree is slightly lower than the slope with the existence of the mature tree. The scenario is the same for the soil matric suction with or without the existence of the mature tree during the prolonged antecedent rainfall (see Figs. 10(a) and 10(b)) that occurred on 20th June 2022 to 26th June 2022.

Based on the soil matric suction recorded during the prolonged dry condition (13th February 2022, 18th February 2022 and 22nd February 2022) presented in Figs. 11 to Figs. 13, the data were analyzed based on the various soil matric suction at a different depth, distance and station with the existence of *Alstonia Angustiloba* mature tree and without the existence of the mature tree. On 13th February 2022 (Slope Area), there is a significant difference between the soil matric suction of the slope without a tree at various depths with the soil matric suction at different depths and distances of the slope with the existence of mature trees on the top as the error bars did not overlap with each other. At the flat area (FA), there are no significant differences between the tree water uptake due to the overlapping of the error bars at various depths and distances. On 18th February 2022 (Slope Area), there is significant differences in tree water uptake between the slope with or without a tree at the top at a different distance except at the deepness of 1.5 m and 2.0 m as the data overlapped with the soil suction of 4.4 m distance. At the deepness of 0.25 m to 2.0 m with various distances from the mature tree, the soil matric suction is significant, except at the deepness of 1.5 m to 2.0 m as the tree water uptake of the slope without the tree is overlapped with the tree water uptake of the slope with the existence of the mature tree at the distance of 4.4 m with a deepness of 1.5 m and 2.0 m. At the flat area (FA), the soil matric suction without the existence of a mature tree is significant to the soil matric suction at various depths and a distance of 2.2 m and 1.1 m. However, coherent to the overlapping error bars between the soil matric suction at the deepness of 0.5 m to 2.0 m, the soil matric suction of the slope without the tree is not significant to the slope with the presence of the tree at the distance of 4.4 m.

On 22nd February 2022, at the SA and FA, the tree water uptake at the slope without a tree is significantly different from the tree water uptake of the slope with the existence of the mature tree at the deepness of 0.25 m to 2.0 m for all depth except at the deepness of 1.5 m and 2.0 m (1.1 m and 4.4 m distance from the mature tree). Based on Fig. 17, most of the FOS value of the slope without the existence of the *Alstonia Angustiloba* mature tree for eight (8) months of field monitoring shows significant differences with the FOS value of the slope with the existence of the mature tree as most of the data did not overlap with each other except when the rainfall precipitation is high which reduce the FOS of the unsaturated slope.

The one-way ANOVA was conducted to examine the mathematical significant difference between the four (4) independent variables (rainfall precipitation, distance of tensiometer from the tree, depth of slope and station area) observed in this study at various conditions (intense rainfall, antecedent rainfall, prolonged antecedent rainfall and prolonged dry condition). Based on the one-way ANOVA, there is a significant difference between the four (4) independent variables (at $P < 0.05$, $P\text{-value} = 2.25 \times 10^{-70}$). Therefore, to specify which parameters contributed to the difference between the means, the Fisher's Least Significant Difference (LSD) was performed as tabulated in Table 3 coherent with the one-way ANOVA conducted. There are six (6) analyses conducted for the LSD; all of the analyses accepted the H_0 (Accept the H_0 claim at Average Difference $<$ LSD, where the $LSD = 0.4147$). The analysis that contributed to the existence of the statistically significant difference is tabulated in Table 3. In reference to Table 3, there is a significant difference between the rainfall intensity with the distance of tensiometers from the tree, depth of the slope and the slope station at a mean difference of 5.83, 7.35 and 7.90 respectively. Moreover, at a mean difference of 1.52 and 2.07, there are also significant differences between the distance of the tensiometers with the depth of the slope and the station area respectively. The differences between the depth of the slope and the station area are also proved at a mean difference of 0.55. The LSD was suggested by Xue et. al., (2021) and Ai et. al., (2021) for the mean separation.

Table 3
Determination of specific parameters that affect the soil matric suction based on Fisher's Least Significant Difference

Mean	Absolute Mean Difference		Remarks
	Mean Diff.	Value	
$\bar{x}_1$	$\bar{x}_1 - \bar{x}_2$	5.83	Difference is significant at $p = 0.05$, $LSD = 0.04147$
	$\bar{x}_1 - \bar{x}_3$	7.35	
	$\bar{x}_1 - \bar{x}_4$	7.90	
$\bar{x}_2$	$\bar{x}_2 - \bar{x}_3$	1.52	
	$\bar{x}_2 - \bar{x}_4$	2.07	
$\bar{x}_3$	$\bar{x}_3 - \bar{x}_4$	0.55	
Note: $\bar{x}_1$, Rainfall Precipitation; $\bar{x}_2$, Distance of tensiometers from Tree; $\bar{x}_3$, Depth of Slope; $\bar{x}_4$, Station Area.			

Table 4 shows the Pearson's correlation coefficient performed to determine the correlation between the variables observed in this study. Ai et. al., (2022) investigated that a correlation value which is below 0.4

is considered as weak correlation, above 0.4 is a strong correlation and no correlation exists with the correlation value reaching zero. Based on the table, there is a very weak correlation exists among the three (3) independent variables (rainfall precipitation, distance of tensiometers from the tree and depth of slope) observed in this study as the correlation value is reaching zero except for the station area showing no correlation exists with the other variables.

Table 4
Determination of the relationship between four (4) parameters studied according to Pearson's Correlation Coefficient

Parameter	A	B	C	D
A	1.0	8.63×10^{-16}	6.94×10^{-17}	0
B	8.63×10^{-16}	1.0	-5.1×10^{-17}	0
C	6.94×10^{-17}	-5.1×10^{-17}	1.0	0
D	0	0	0	1.0
Note: A, Rainfall Precipitation; B, Distance of Tensiometers from the Tree; C, Depth of Slope; D, Station Area.				

4. Conclusions

This investigation examines the effect of the *Alstonia Angustiloba* tree at top of the slope on the tree water uptake dispersions on tropical residual soil. The tree water uptake profile arrangement in soil mass is subjected to increase owing to tree water uptake and to decrease due to rainfall. Appertaining to the investigation performed, the deduction can be drawn as follows:

- a. The modifications in tree water uptake, especially on a slope with a tree at the top were obviously divergent from the slope without a tree. This investigation provided the benefaction of a mature tree which substantially altered the tree water uptake in tropical residual soils slope. During this course of study, several changes in the climatic conditions resulted in variations in tree water uptake profiles were found. At the slope with a tree at the top, the variations of the matric suction profiles were very large. Consequently, for slopes without trees, the variation of the tree water uptake profiles was less significant.
- b. The normal range of cutting slope arithmetic and the tree location at the top of the slope has been considered. The matric suction profiles at a certain depth and distance from the tree have been presented and illustrated which were used for further integration with the slope. The slope with matric suction contour at various times has been shown with values from the matric suction profiles. These served to illustrate the tree water uptake that was created by the mature tree and reached its maximum value throughout the proximity of the mature tree. Summarized from that, this proved how a single mature tree can greatly contribute to water extraction from the residual soil. Therefore, the

explorations of this research proved that the moisture variation or the matric suction has been altered via the transpiration process in an unsaturated soil slope.

- c. The comparison of the FOS for six (6) months period has been made between the slope with and without a tree at the top. Based on the results obtained, showed that mature trees induced acceleration to increase the tree water uptake. The results also indicated that FOS may increase up to 53.00% above the values obtained from the slope without the tree where the FOS value at the slope with the tree is 4.57 and the FOS value at the slope without the tree is 2.17. The influence of tree roots zone was taken into account which lead to the improvement of soil properties for development in geotechnical slope designs. Obviously, this attribution influence the overall slope stability and awareness of tree preservation in the community should be taken seriously.
- d. Based on the error bars plotted, juxtapose to the slope without the tree, the existence of the *Alstonia Angustiloba* tree on the top of the slope does affect the FOS value of the tropical residual soil slope significantly. Moreover, Pearson's correlation coefficient proved that there is no correlation between the rainfall intensity, distance of tensiometers from the tree, depth of slope and the station area.

The study, therefore, concludes that the *Alstonia Angustiloba* mature tree firmly influenced the geotechnical engineering properties of the tropical residual soil slope as an effective slope stabilization via the tree water uptake method. The utilization of the *Alstonia Angustiloba* mature tree contributed to the improvement of the FOS up to 53.00% from the FOS value of 2.17 to 4.57 as compared to the slope without a tree.

Declarations

Ethical Approval

Not Applicable

Consent to Participate

Not Applicable

Consent to Publish

Not Applicable

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Authors Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Muhammad Syamsul Imran Zaini, and Muzamir Hasan and Muhammad Farhan Zolkepli. The first draft of the manuscript was written by Muhammad Syamsul Imran Zaini and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript

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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.

Availability of data and materials

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

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Figures

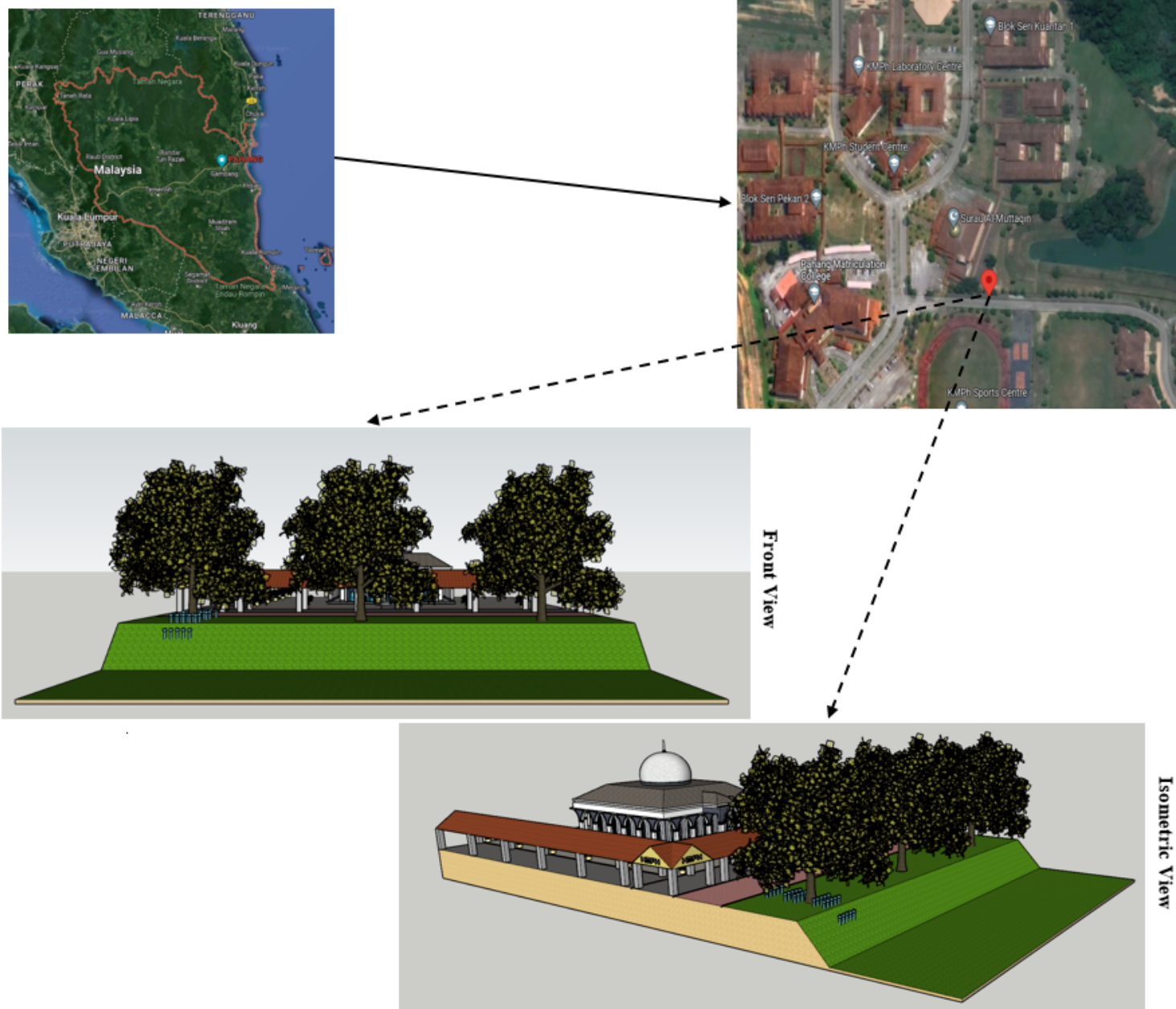


Figure 1

Location of kaolin clay and bottom ash used in this study. ERI, Electrical Resistivity Imaging; FA, Flat Area; and, SA, Slope Area

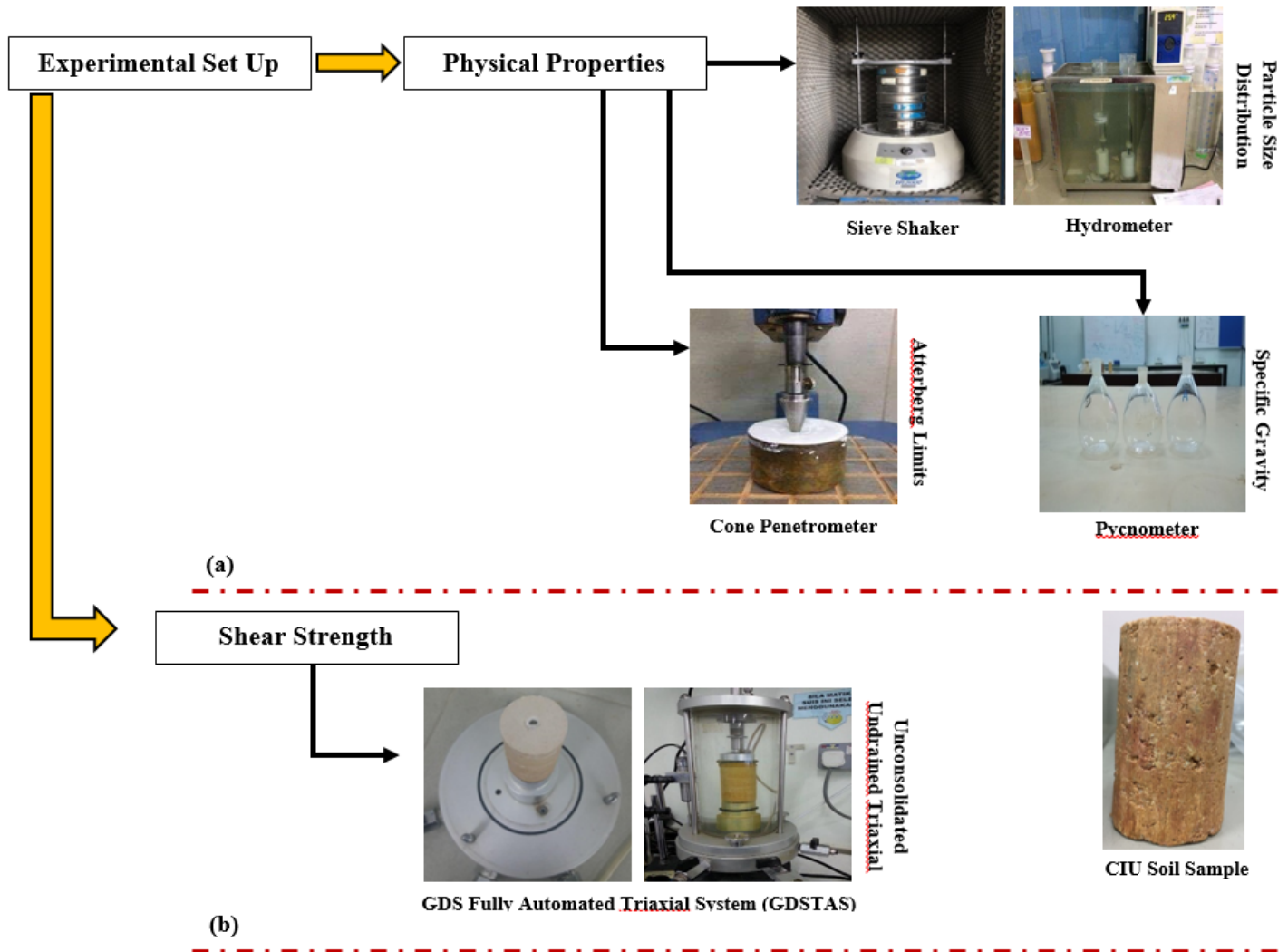


Figure 2

Experimental setup in determining: a) physical properties of tropical residual soil; and, b) shear strength of tropical residual soil

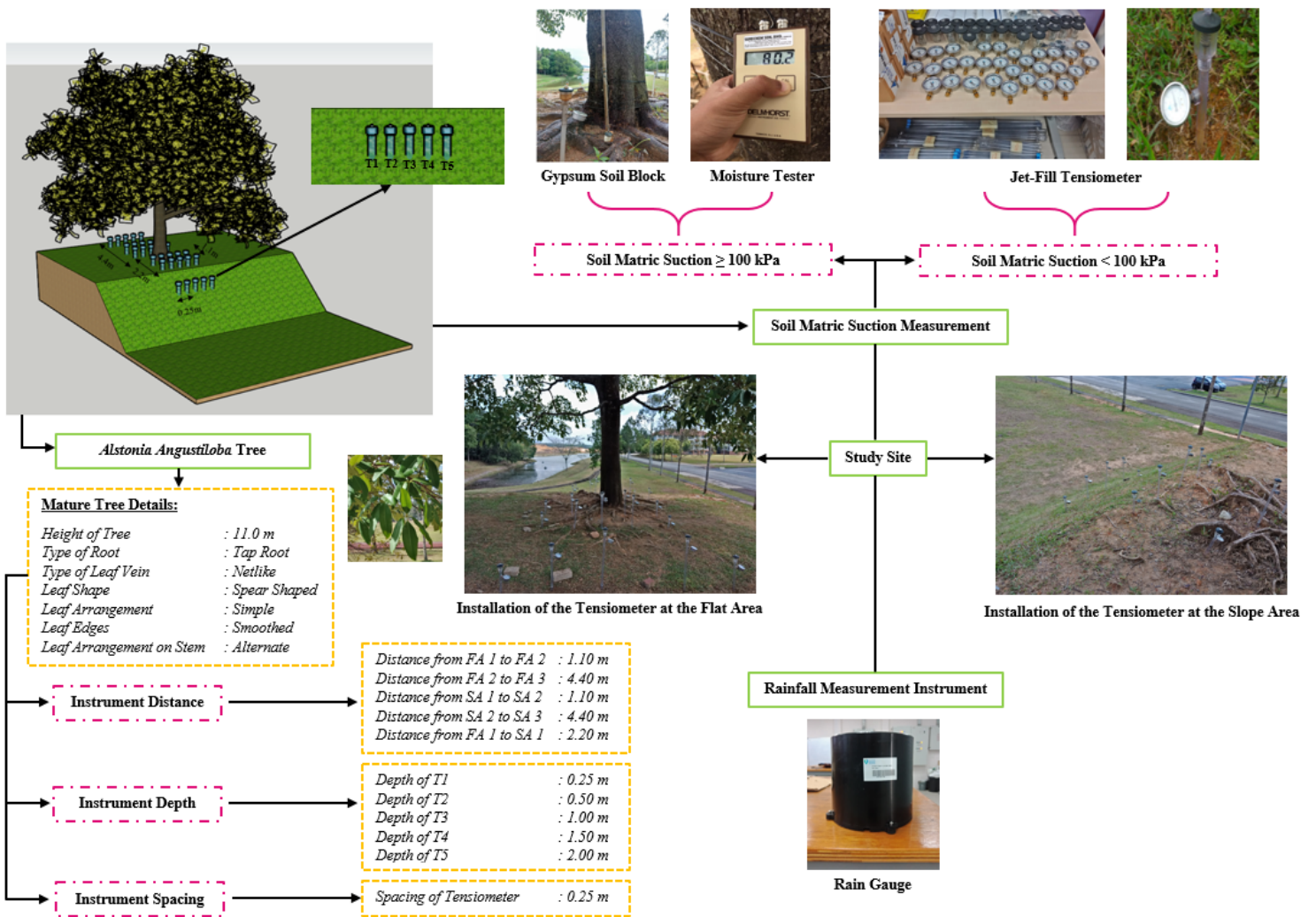


Figure 3

Experimental setup in determining the soil matric suction and rainfall intensity

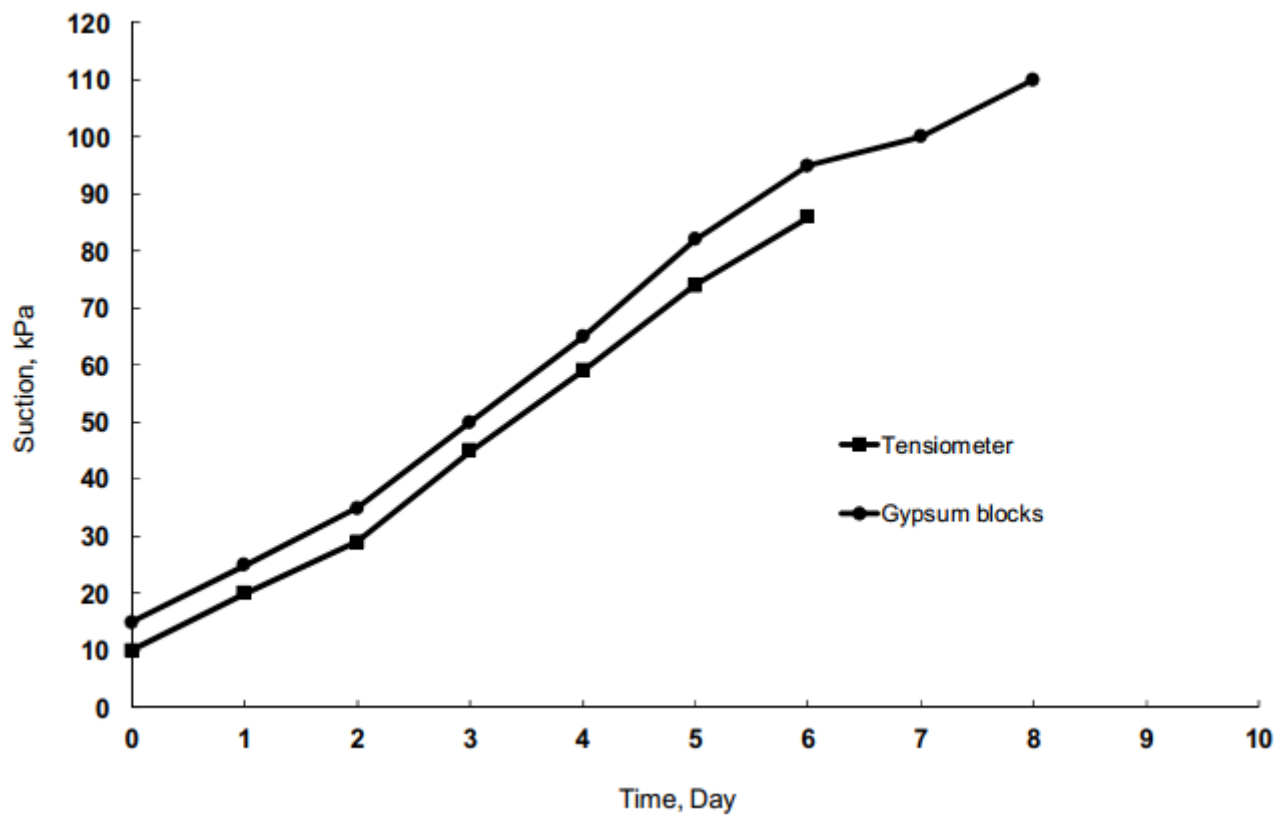


Figure 4

Calibration and capability of Tensiometer and Gypsum Block

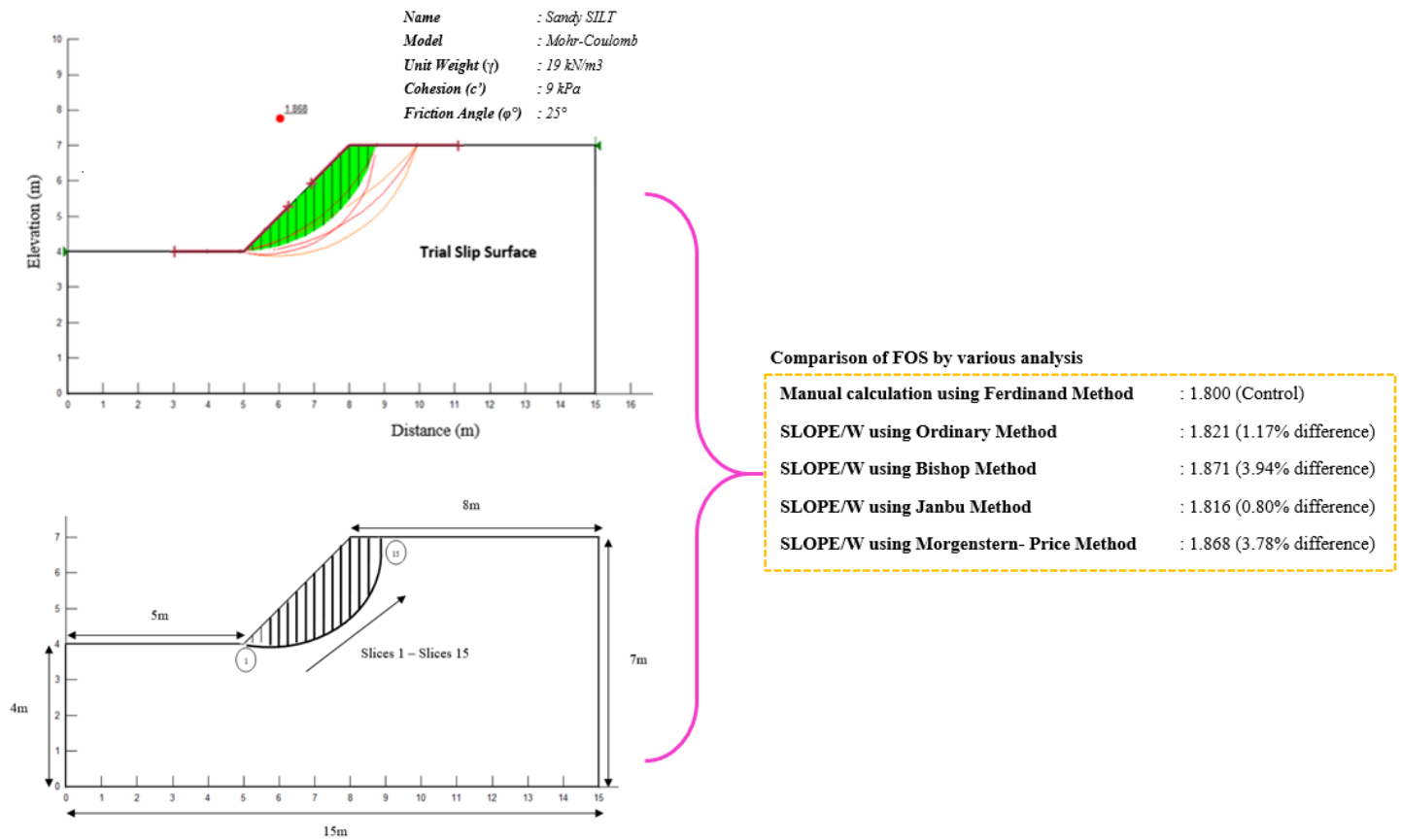


Figure 5

Slope Geometry of the Tropical Residual Soil with the Comparison of FOS by Various Analysis.

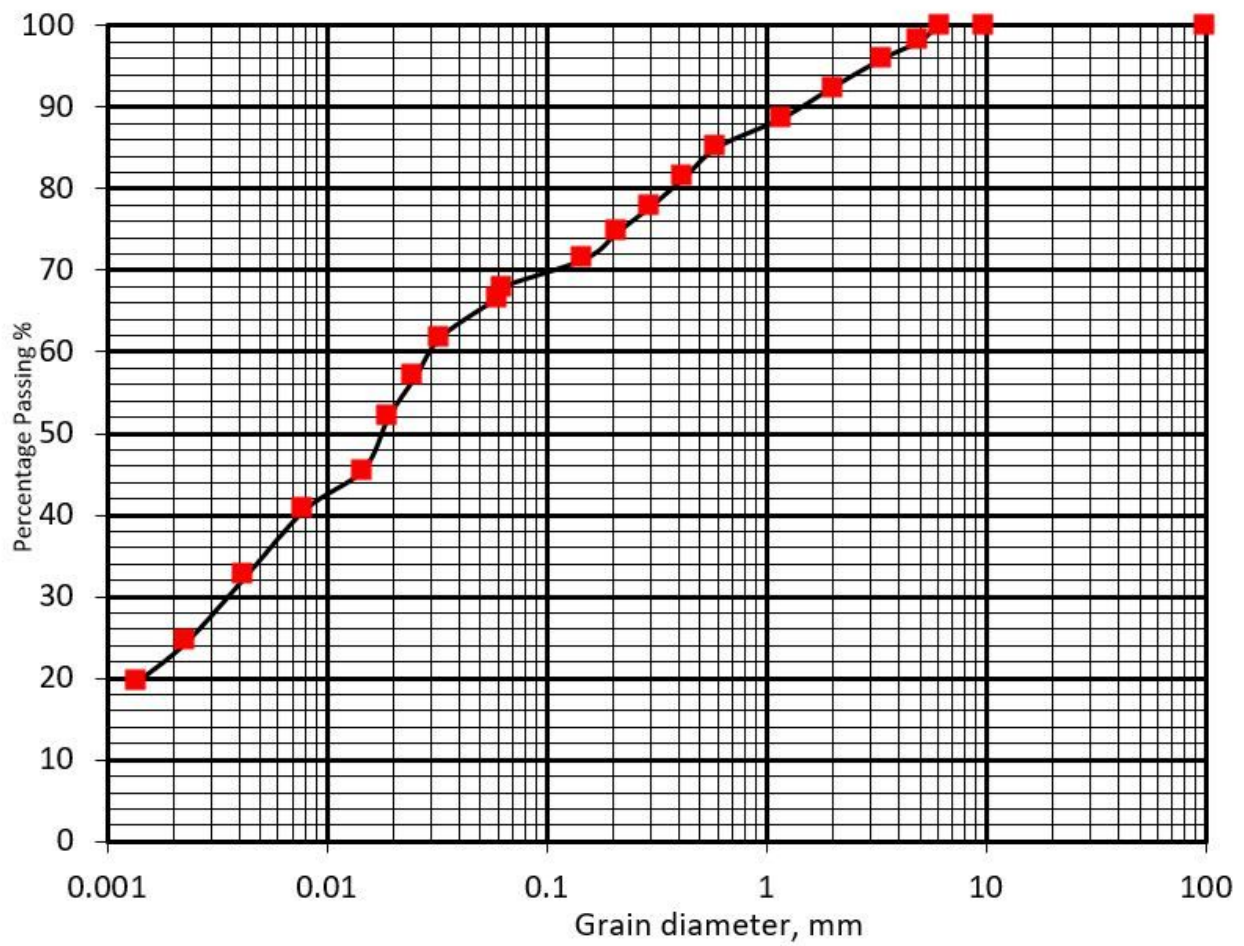


Figure 6

Particle Size Distribution Graph of Tropical Residual Soil.

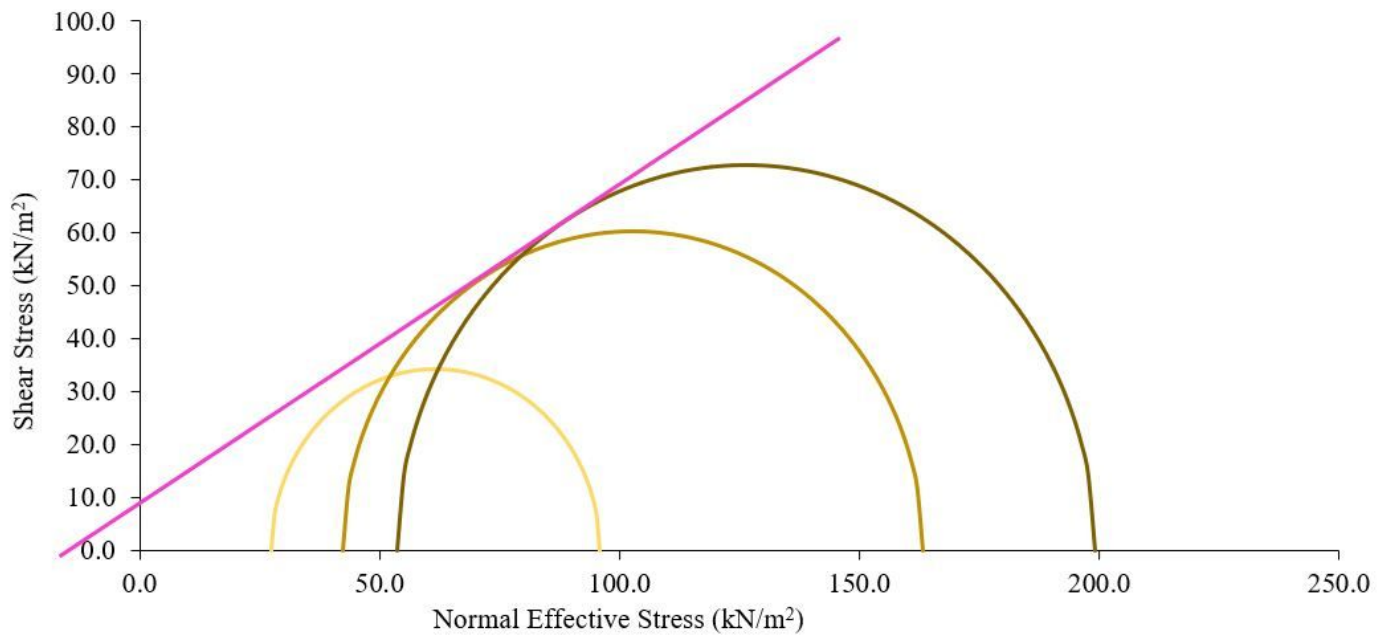


Figure 7

Mohr's Circle and the effective stress failure envelope of Tropical Residual Soil.

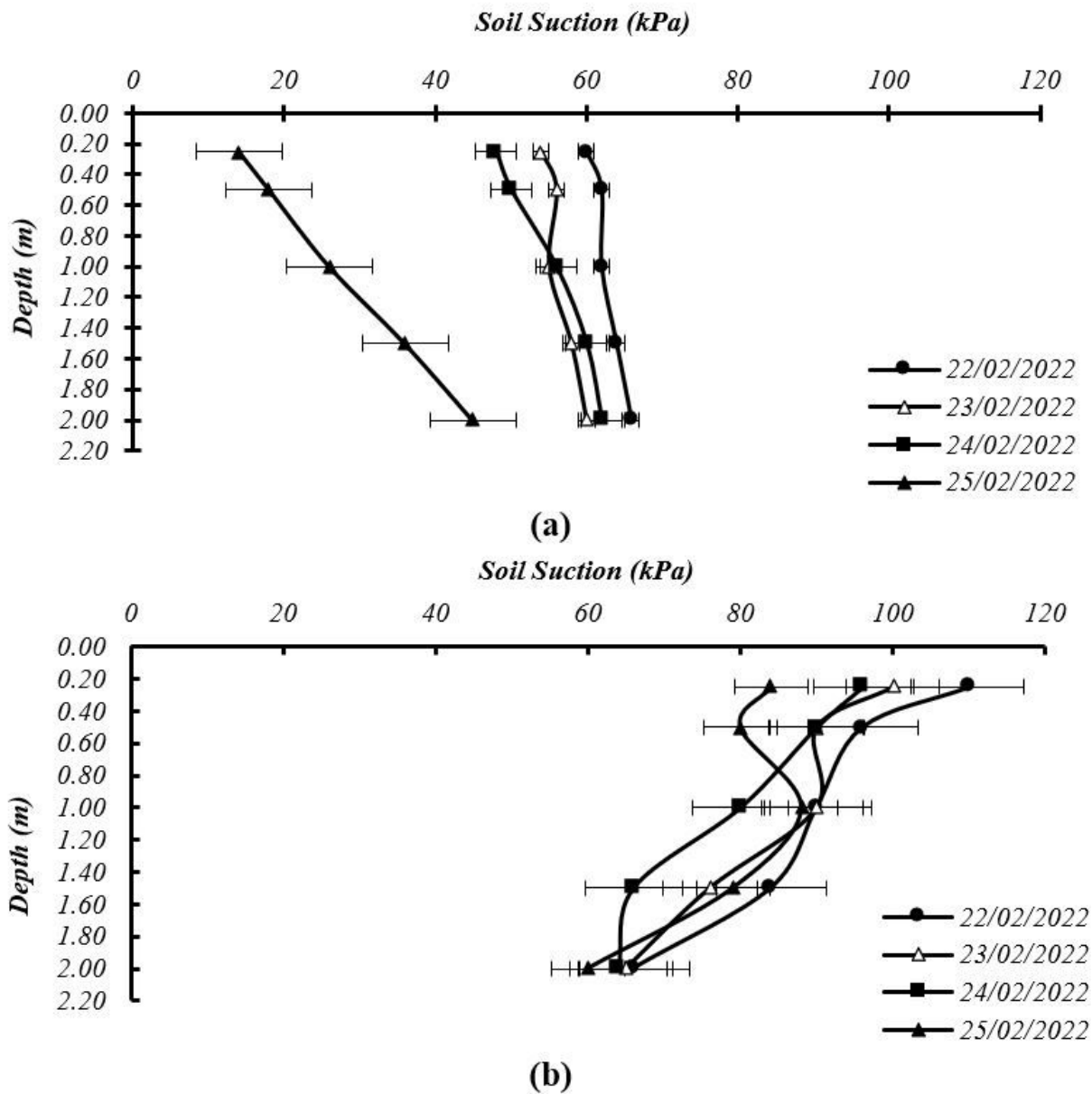
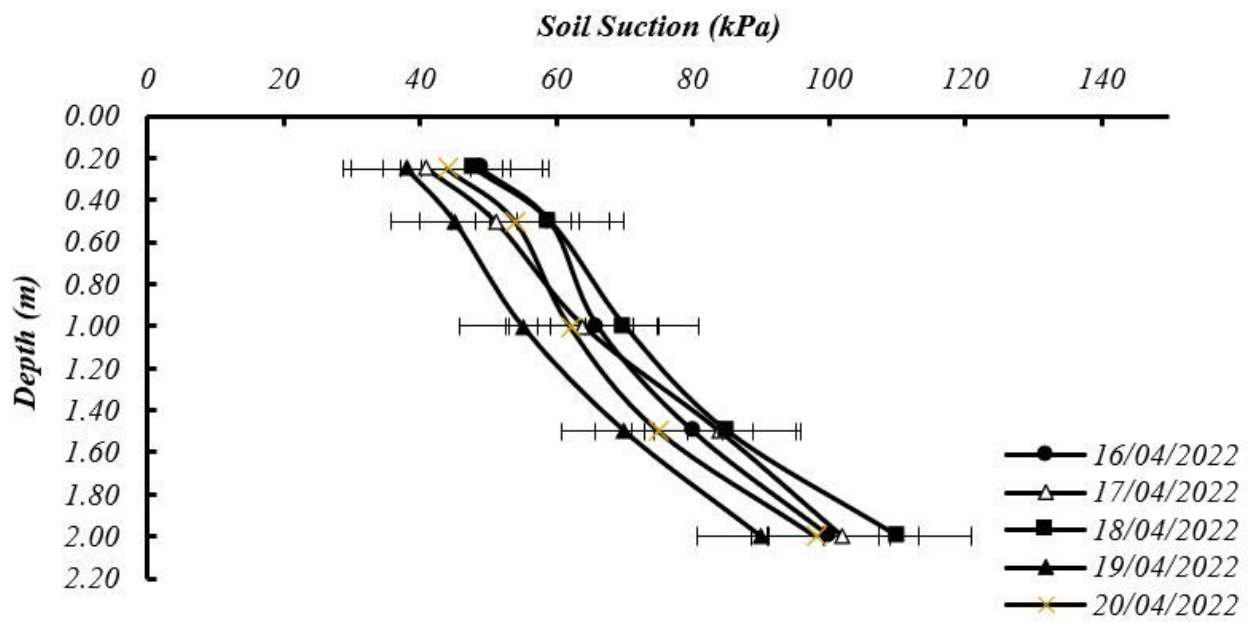
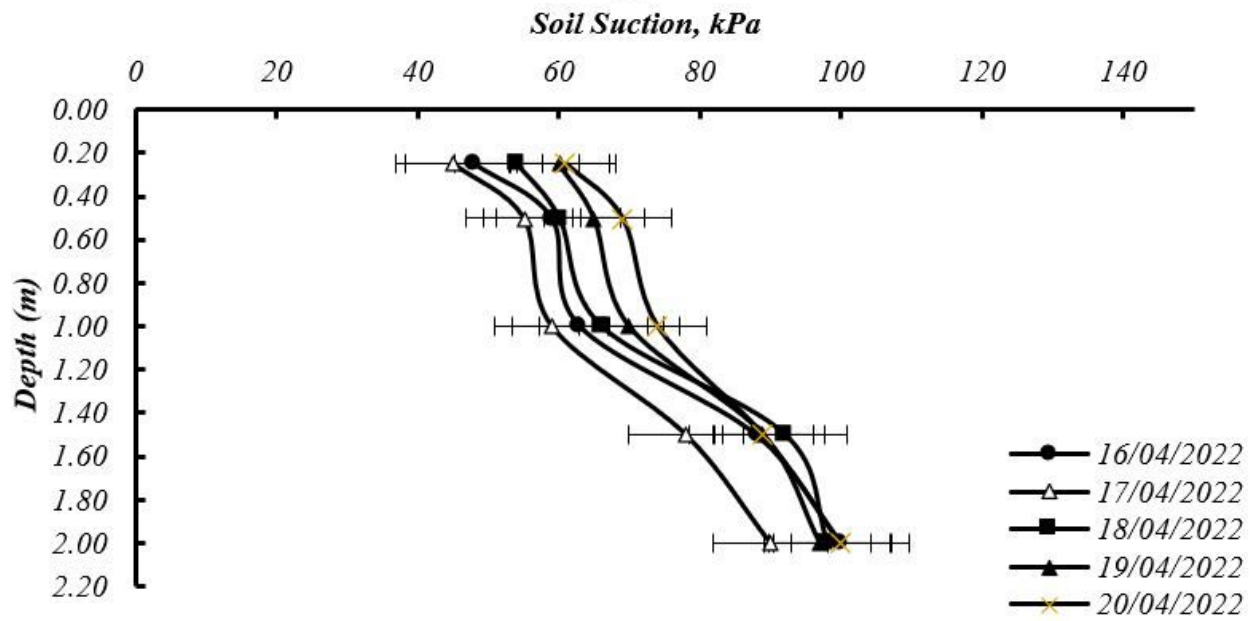


Figure 8

Soil Matric Suction with Respect to the Intense Rainfall Precipitation at: a) Slope without the tree; b) Slope with *Alstonia Angustiloba* mature tree.



(a)



(b)

Figure 9

Soil Matric Suction with Respect to the Antecedent Rainfall Precipitation at: a) Slope without the tree; b) Slope with *Alstonia Angustiloba* mature tree.

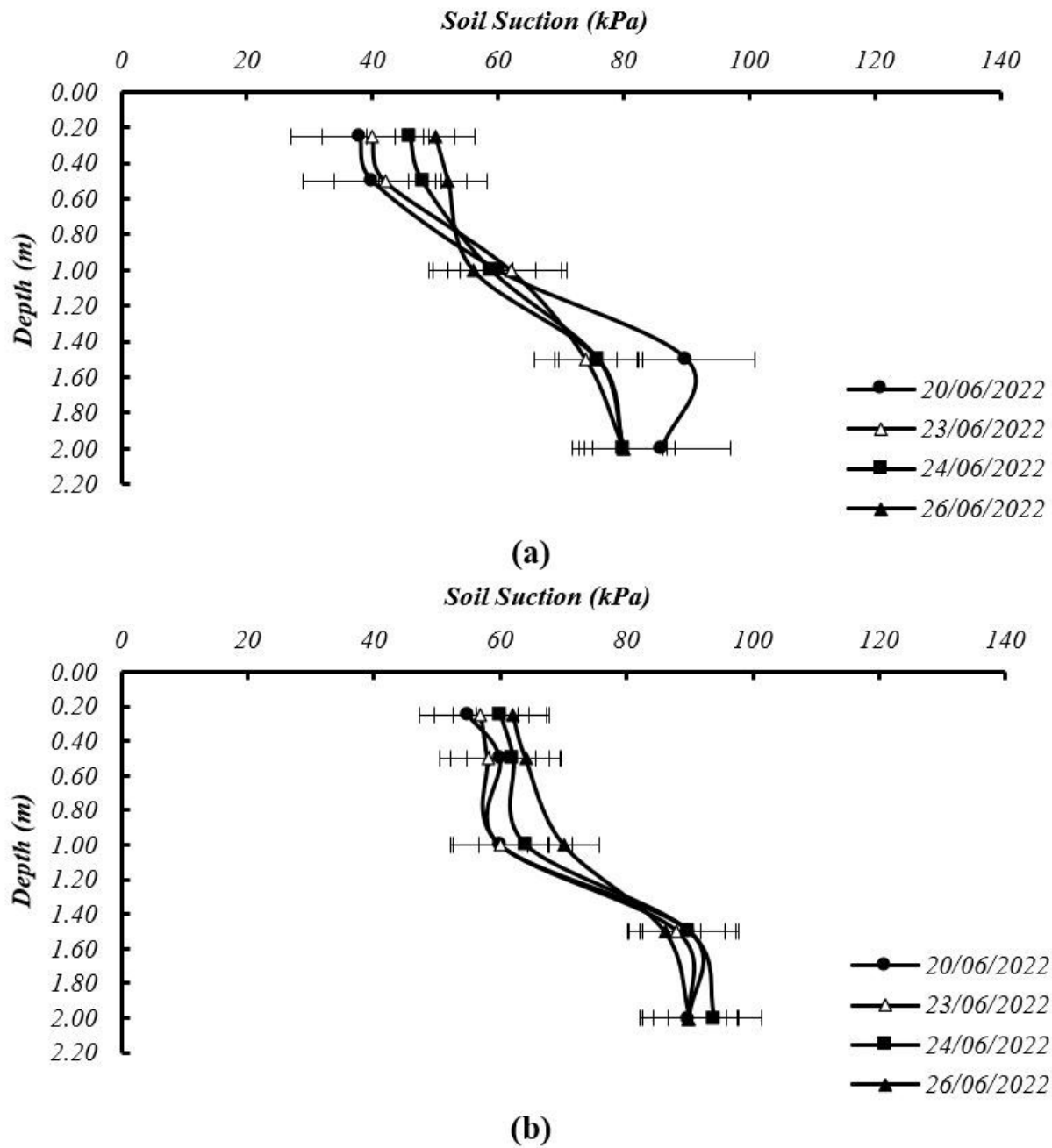
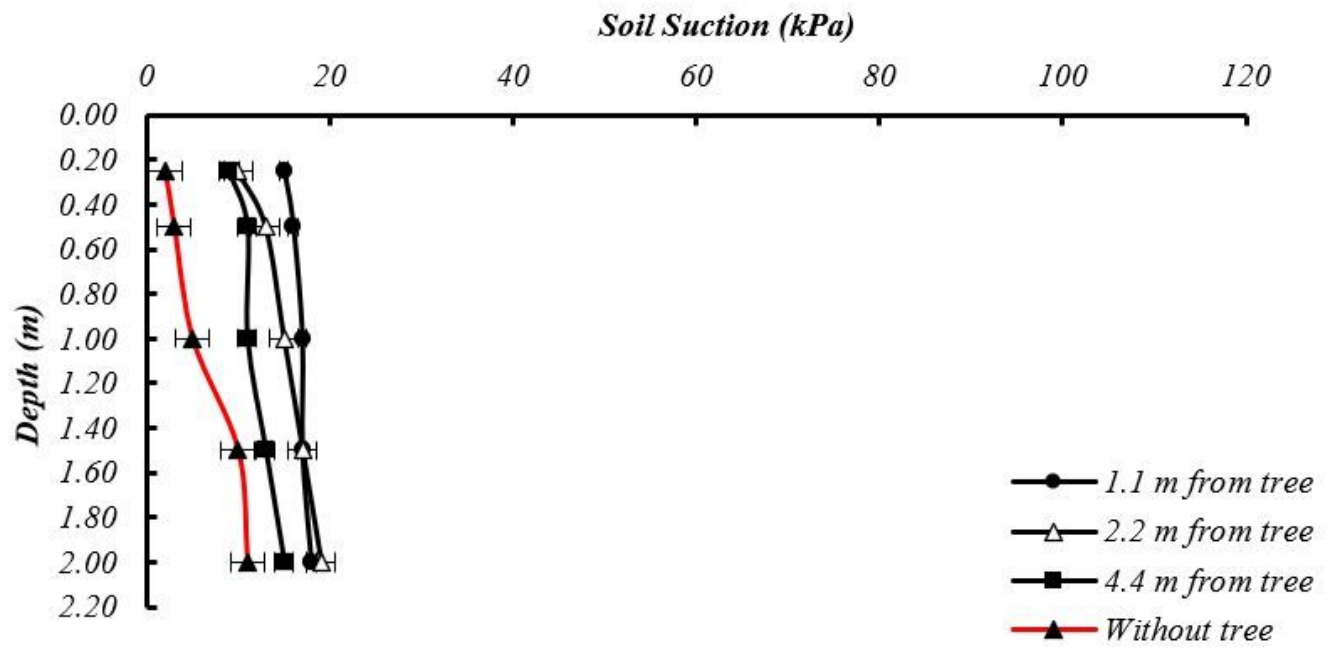
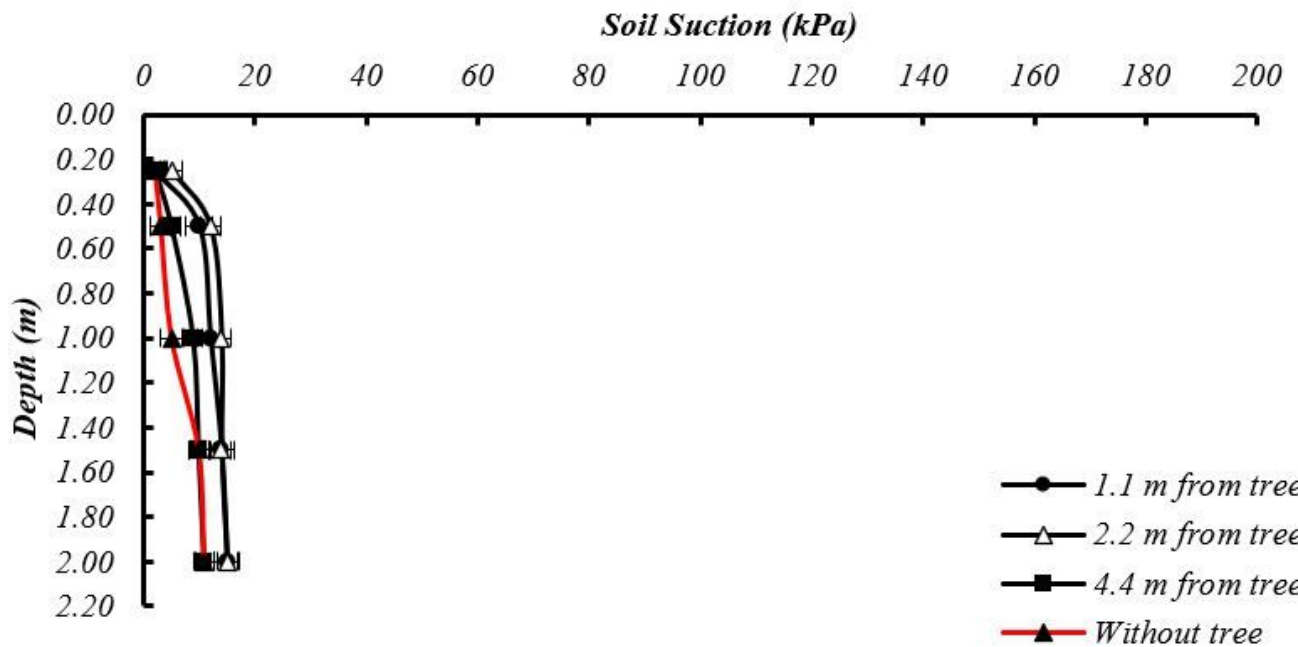


Figure 10

Soil Matrix Suction with Respect to the Prolonged Antecedent Rainfall Precipitation at: a) Slope without the tree; b) Slope with *Alstonia Angustiloba* mature tree.



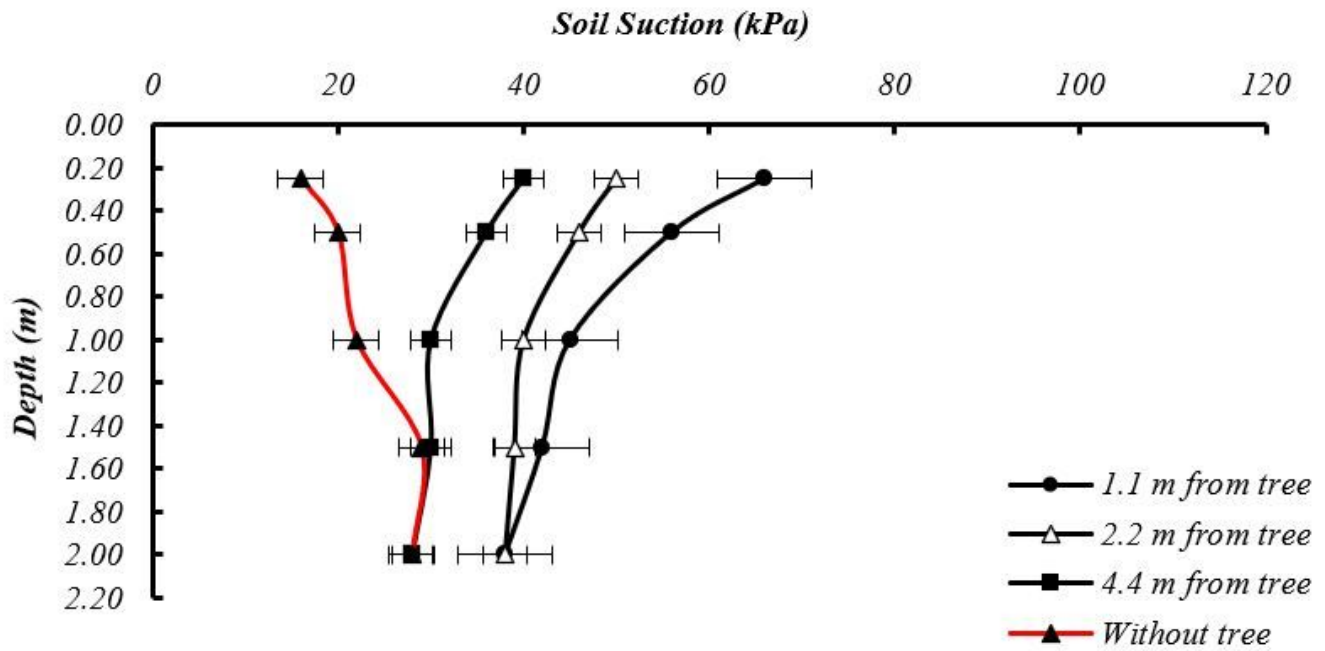
(a)



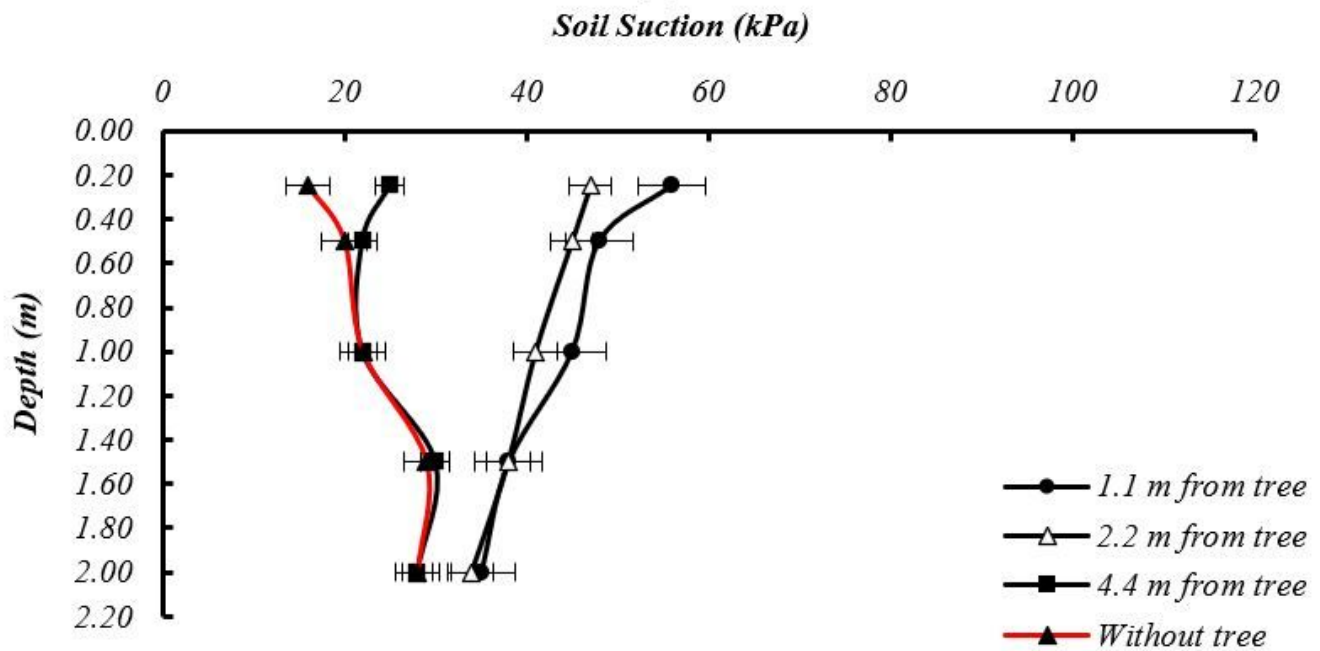
(b)

Figure 11

Soil Matric Suction with Respect to the Prolonged Dry Condition on 13th February 2022 in: a) Slope Area; b) Flat Area.



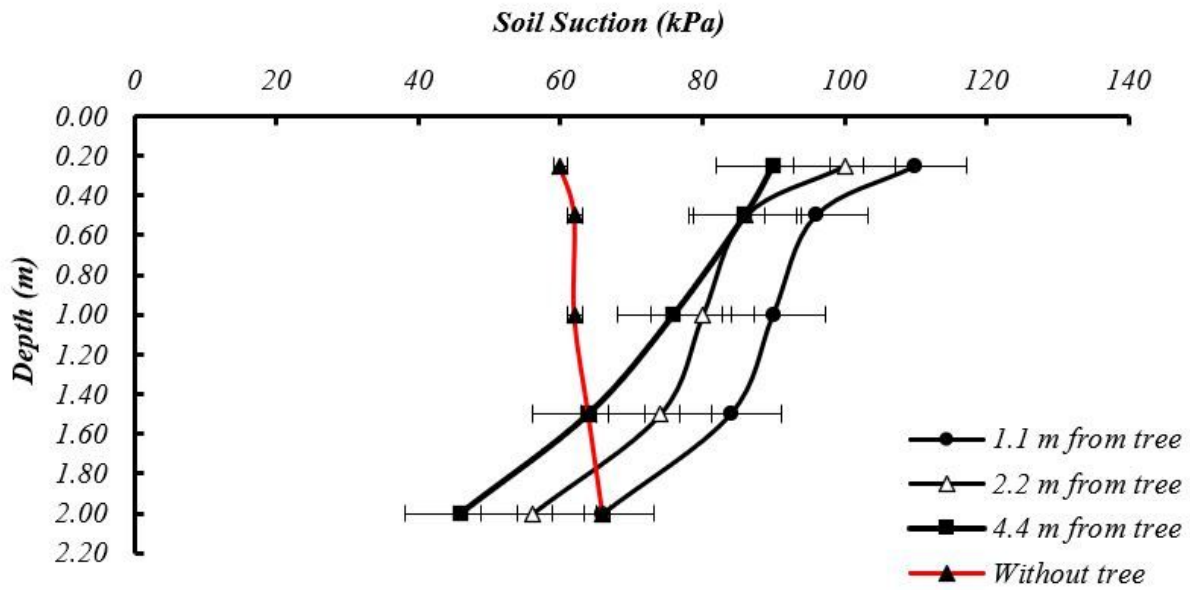
(a)



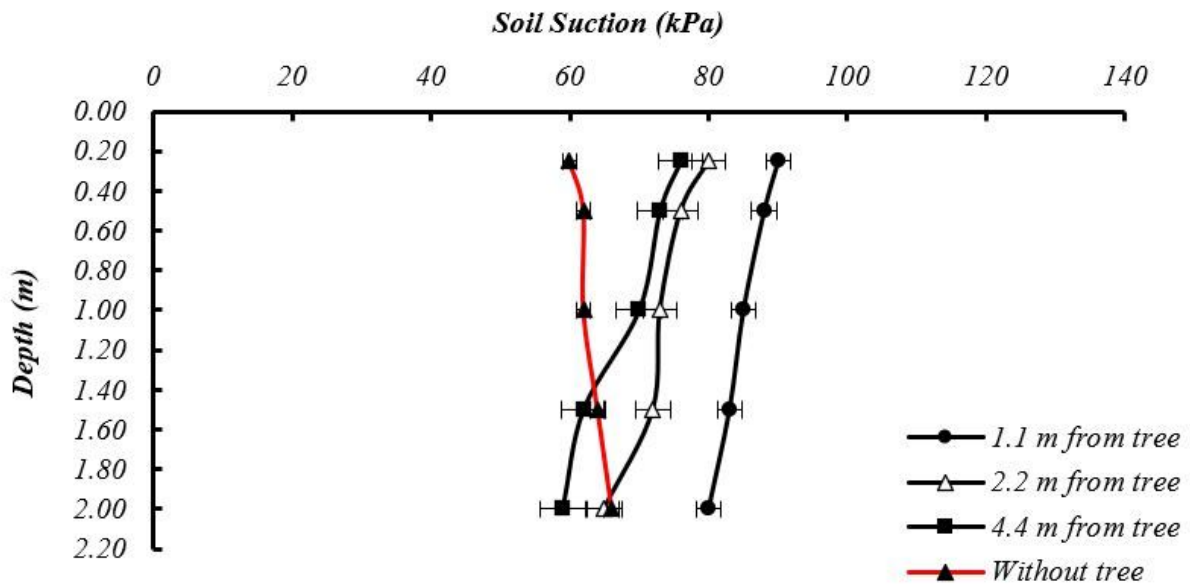
(b)

Figure 12

Soil Matrix Suction with Respect to the Prolonged Dry Condition on 18th February 2022 in: a) Slope Area; b) Flat Area.



(a)



(b)

Figure 13

Soil Matric Suction with Respect to the Prolonged Dry Condition on 22nd February 2022 in: a) Slope Area; b) Flat Area.

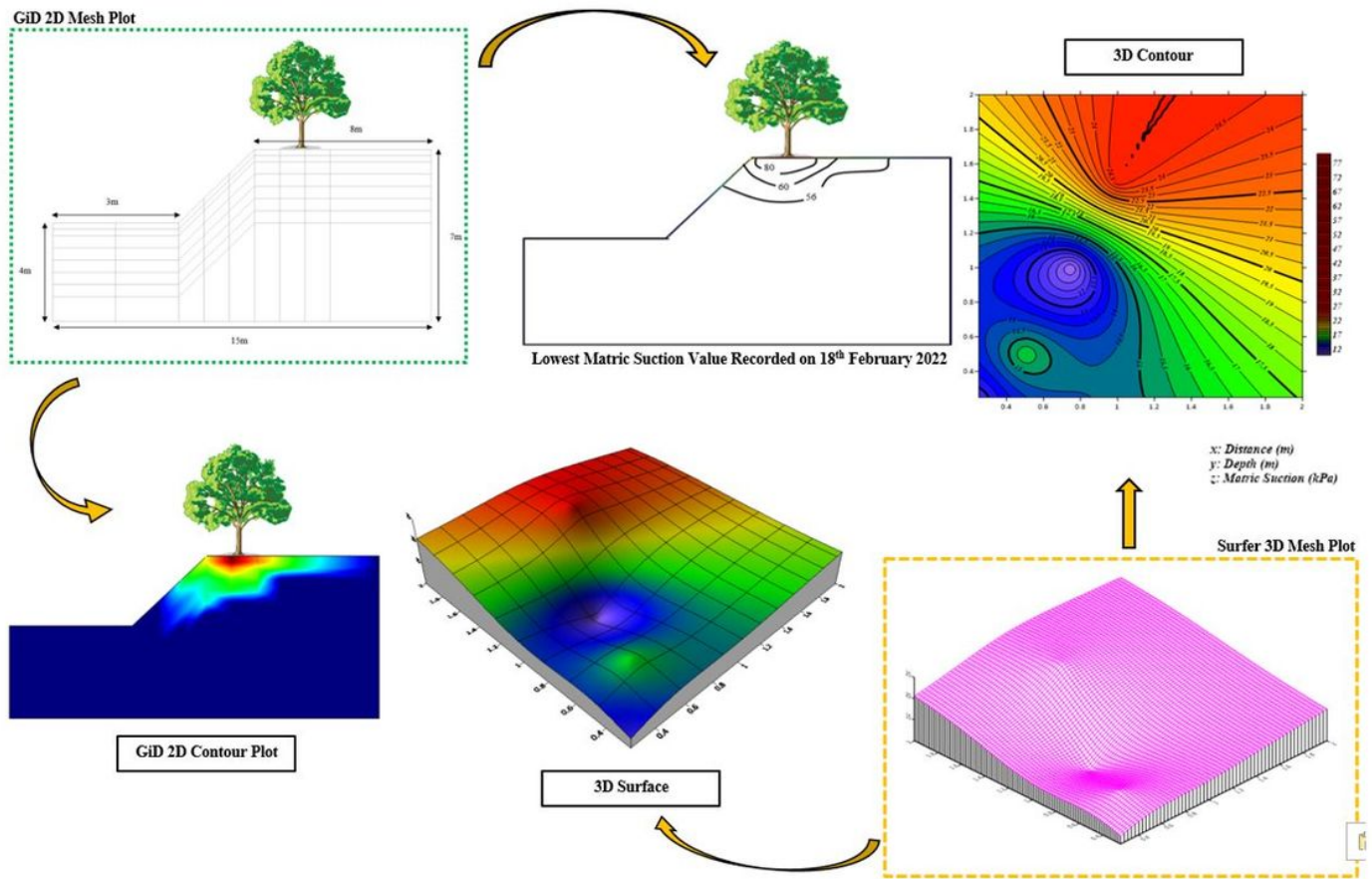


Figure 14

Soil matric suction (kPa) contour corresponds to the lowest soil matric suction throughout eight (8) months of field monitoring on the Tropical Residual Soil Slope

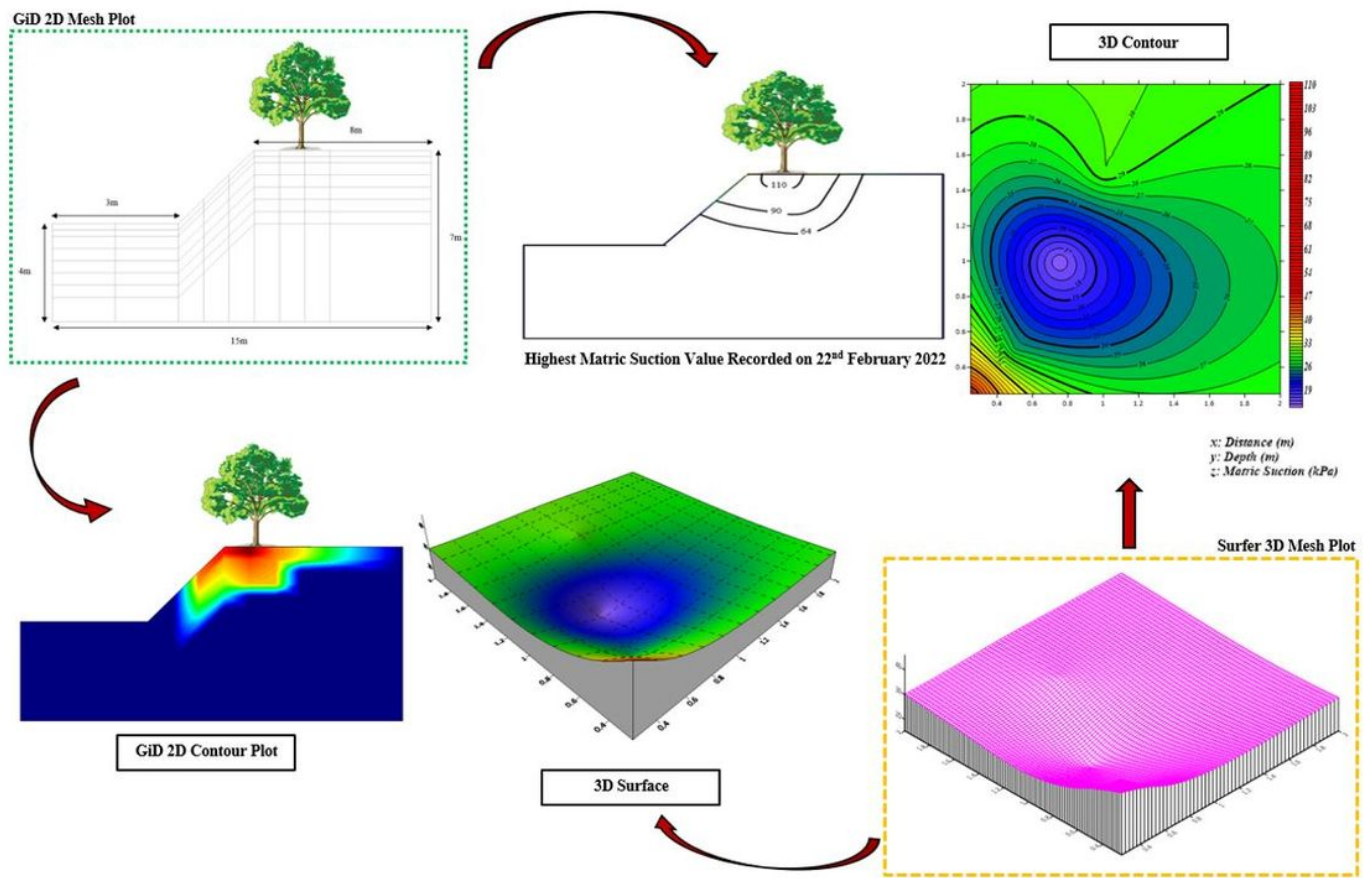


Figure 15

Soil matric suction (kPa) contour corresponds to the highest soil matric suction throughout eight (8) months of field monitoring on the Tropical Residual Soil Slope

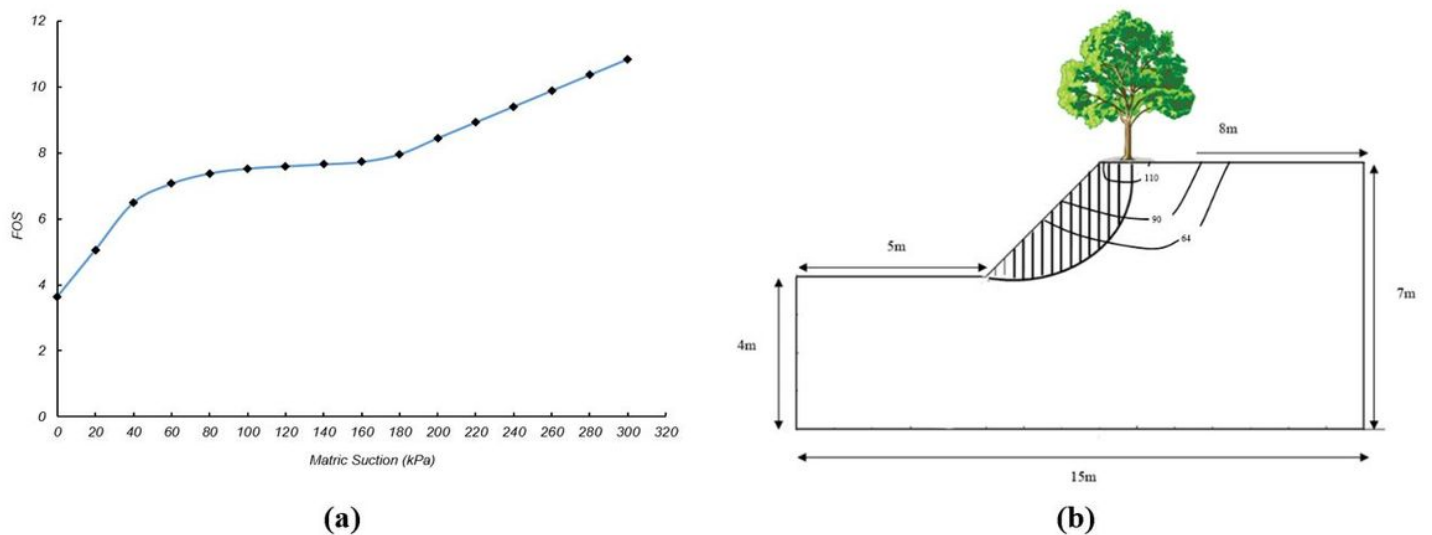


Figure 16

Relationship between a) Proportionality of matric suction with FOS; (b) Matric suction with critical slip surfaces for FOS calculations.

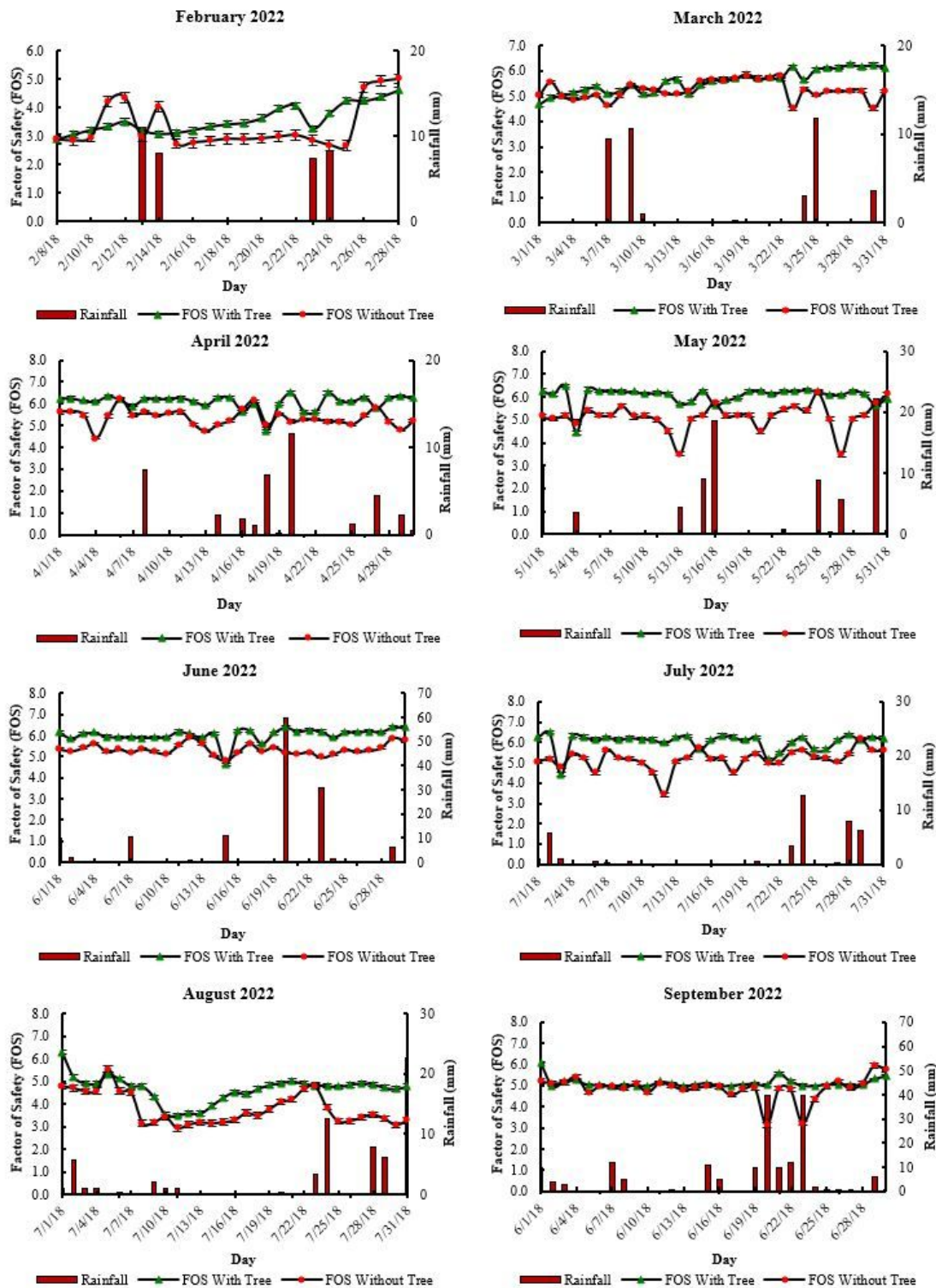


Figure 17

Soil matric suction variations with a critical slip surface and slices on tropical residual soil slope with and without the existence of *Alstonia Angustiloba* mature tree