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Verification of tree induced suction with numerical model

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ABSTRACT

This study discusses the validation between explorations of transpiration on the unsaturated soil zone with unsaturated flow equation of tree water uptake model. Numerical simulation was performed to the model of the slope in relation to moisture migration patterns in the unsaturated zone within the vicinity of mature tree. The results of numerical simulation conducted on typical slope geometry model with tree at the toe of the slope of induced transpiration were later presented in this study. The results of numerical simulation and field monitoring of suction against depth are in acceptable condition. It is important to note that, several of the differences between simulated numerical and field measurement are related to inconsistence effect of root density.

1. Introduction

Nowadays, green slope engineering which basically implement the use of live vegetation can be considered as cost-effective and environmental friendly which already been implemented by engineers (Operstein and Frydman, 2000; Zhu et al., 2017). Some people considered slope with vegetation only have minor effect against slope stability. However, in some cases, this assumption is not appropriated (Kokutse et al., 2016). As suggested by Zaini et al. (2020), tree water uptake gives high significant effect to increase and maintain slope stability.

1.1. Slope stability

In order to maintain slope stability, soil bioengineering using vegetation had well-known recognised as an environmental friendly engineering method (Ni et al., 2018). Previous researchers (Wu et al. (1979); Pollen and Simon (2005); Fan and Su (2008); Jotisankasa and Taworn (2016)) had included the effect of mechanical root reinforcement and this usually relates to slope stability calculation (Greenwood et al. (2004); Genet et al. (2010); Jotisankasa et al. (2014); Mao et al. (2014); Zhu et al. (2017)). According to Gray (1996) and Stokes et al. (2005), the used of vegetation for improving slope stability is a popular method used worldwide because it proves to prevent from landslides and slope instability.

1.2. Tree water uptake

Vegetation plays a very important role to maintain slope stability since tree helps to decrease the moisture content in soil, thus will increase the shear strength of the slope itself (Ali, 2007; Ishak, 2014; Zolkepli et al., 2018; Yue et al., 2019; Goh et al., 2020; Zaini et al., 2020). The root will absorb water from the soil to be use in photosynthesis process together with sunlight. The water from the soil such as soil water, irrigation water, rainfall and groundwater are all absorbed by plant roots (Shi et al., 2003; Sun et al., 2005; Cao et al., 2018). Plants are able to absorb water through roots from surface water or deep water (Ehleringer and Dawson, 1992; Corneo et al., 2018). As suggested by Biddle (1998) and Briggs et al. (2016), for an embankment slope which usually less than 10 m height, trees can generate suction of 1500 kPa up to 2–3 m depth.

1.3. Soil-water characteristic curve

The actual data ranges of suction obtained from the field monitoring yield reasonably within those determined from the analysis of SWCC. In fact, there are many numbers of shear strength equations that have been published to predict the shear strength of unsaturated soil based on SWCC as the controlling parameter. The basis to the relationship between the unsaturated shear strength behaviours with SWCC presented

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by Vanapalli et al. (1996) and Fredlund et al. (1996). The following section discusses the issues that related to any attempt to compare and fit the experimental results with the nonlinear failure envelope (shear strength envelope) proposed by Fredlund et al. (1996).

1.4. Numerical model

In this paper, numerical simulation was performed to the model of the slope in relation to moisture migration patterns in the unsaturated zone within the vicinity of mature tree. The simulation suction distributions were verified with those of field measurements (suction monitored at study area) to identify the most similar or adequate approach that best fit the field data set (Ishak, 2014). The numerical model approach adopted utilizes radial symmetry and assumes a linear distribution of water extraction rates with both depth and radius. Apart from verification using numerical simulation, consideration of the matric suction pattern profile of field monitoring during several dry periods revealed continuum cycle of significant increasing matric suction. Further examination to justify the similar dry pattern (high matric suction) generated by active root tree will be discussed later.

The results from field monitoring presents the influence of tree water uptake on the matric suction profile distributions of an unsaturated slope on tropical residual soil. The moisture migration is revealed by matric suction changes through field observation. The aim of this paper is to discuss the validation between explorations of transpiration on the unsaturated soil zone with unsaturated flow equation of tree water uptake model. This is not an easy task but not impossible to fit between actual fields monitoring results and simulation results from numerical model study.

2. Research methodology

This section discusses the methodology used to conduct this research. All instruments needed for field monitoring work are presented in this section.

2.1. Instruments for soil suction collection (field monitoring)

Three instrument used in this research which conducted by Ishak (2014) and Ishak et al. (2016) were tensiometer, gypsum block and rain gauge. Fig. 1 show all the equipment used to measure soil suction (field monitoring work) at study area.

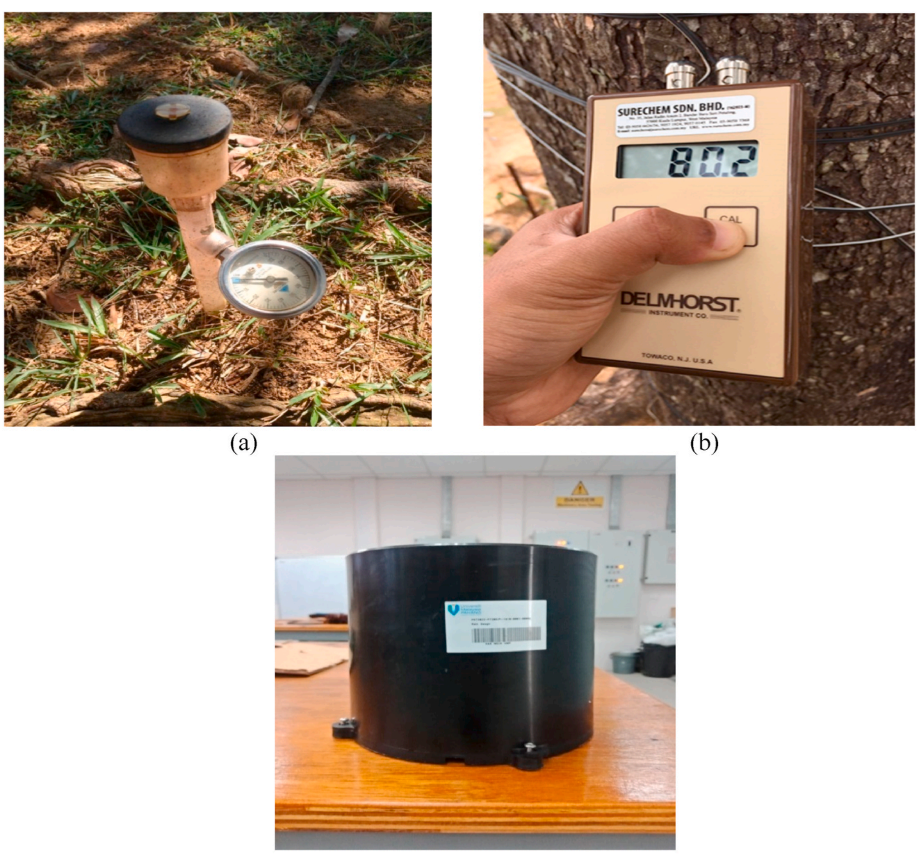
Tensiometers were used to measure suction (0–100 kPa) while gypsum blocks measure suction (100–1500 kPa) generated at vicinity of tree located at toe of slope. Rain gauge used to measure the amount of rainfall at study area.

2.2. Soil-water characteristic curve (SWCC)

In this study, soil-water characteristic curve (SWCC) was determined by increasing the air pressure (μ_α) inside the apparatus while maintaining pore water pressure (μ_w) at atmospheric. This technic was based on axis translation suggested by (Simms and Yanful, 2004). Fig. 2 show the SWCC test conducted at Universiti Putra Malaysia.

2.3. Numerical model

The current work is based on field exploration of moisture uptake compared to the numerical simulation of moisture migration pattern. In this approach, the flow equation of two-dimension axisymmetric water uptake equation developed by Ali (2007) with a pre-defined root zone



(a) (b) (c)

Fig. 1. (a) Tensiometer (b) gypsum block reader (c) rain gauge.

Fig. 2. Pressure plate extractor test setup in Universiti Putra Malaysia.

was employed in this analysis. In this zone, the moisture will be migrating due to extraction rate produced by determined root density, transpiration demands amongst other factors. This type of behaviour is best represented by volumetric sink term included in the unsaturated flow equation. This term can simply be included into equation (1.1) to yield:

$$C(\psi)\frac{\partial\psi}{\partial t}=\frac{\partial}{\partial r}\left[K(\psi)\frac{\partial\psi}{\partial r}\right]+\frac{\partial}{\partial z}\left[K(\psi)\frac{\partial\psi}{\partial z}\right]+\frac{\partial K(\psi)}{\partial z}+\frac{1}{r}K(\psi)\frac{\partial\psi}{\partial r}-S \tag{1.1}$$

The sink term, S, is expressed as the volume of water per unit volume of soil per unit time (cm^3 water. cm^{-3} soil. sec^{-1}). However, in order to be able to make use of equation (1.1) to simulate water uptake by roots, Ali (2007) has defined the sink term a manner that will adequately related to the water extraction process in the root-zone. The extension of Prasad's (1988) approach was presented here as a similar logic for the applied for development a procedure that is applicable to solve two dimensional axi-symmetric problems. Cutler and Richardson (1989) studied the relationship between root spread and the height of trees.

They suggested that root spread for a single tree should be symmetry, approximately similar for both depth and radius. Biddle (1998) measured the effect of water uptake through soil moisture deficit profile for a range of different trees species during several year of research in the UK. This study already presented that moisture migration occurred within the vicinity of trees and demonstrated that as the radial distance from the trunk of the tree increases, the water extracted by the roots started to deplete. In view of this current work, several assumptions have been made:

i. Root water extraction is maximum when directly beneath the tree.
ii. A linear relationship between root water extraction and radial distance is assumed.
iii. Root water extraction becomes zero at some maximum radius.

The relationship between radial distance and root water extraction is introduced via a simple linear grading of the total transpiration radially over the active root zone. Using similar logic to that employed by Prasad (1988), it is assumed that the distribution of potential transpiration in radial direction, T_j is given by,

$$T_j=c_j-d_jr \tag{1.2}$$

where $c_j$and $-d_j$are the intercept and slope on the jth day, respectively and r is the rooting radial distance. At the end of the root zone (i.e. at $r=r_j$) the boundary condition is $T=0$ and therefore:

$$c_j-d_jr_{rj}=0 \tag{1.3}$$

The total transpiration, T, across the root zone is then obtained by integrating over the active depth i.e.

$$T=\int_0^{r_{rj}}T_j\partial r \tag{1.4}$$

Combining equation (1.2) and (1.4) give:

$$T=\int_0^{r_{rj}}(c_j-d_jr)\partial r \tag{1.5}$$

Integrating Equation (1.5) yields:

$$T=c_jr_{rj}-\frac{d_jr_{rj}^2}{2} \tag{1.6}$$

At the end of root zone:

$$c_j=d_jr_{rj} \tag{1.7}$$

Substituting equation (1.7) into equation (1.6), yields

$$d_j=\frac{2T}{r_{rj}^2} \tag{1.8}$$

Substituting equation (1.8) into equation (1.7), then give

$$c_j=\frac{2T}{r_{rj}} \tag{1.9}$$

Combining equations (1.2), (1.8) and (1.9) give:

$$T_j=\frac{2T}{r_{rj}}-\frac{2T}{r_{rj}^2}r \tag{1.10}$$

This can be re-arranged as:

$$T_j=\frac{2T}{r_{rj}}\left(1-\frac{r}{r_{rj}}\right) \tag{1.11}$$

From a review on moisture requirements and the effects of pressure head on yield and quality of various vegetable crops, Feddes et al. (1976) concluded that in general, the pressure head for these crops at which soil water begins to limit the plant growth is about -400 cm. Therefore, the water uptake by roots is constant and at a maximum rate for -400 cm (h_2) $<\psi<-50$ cm (h_1). The water uptake for the plant, is assumed to decrease linearly between $h_3=-400$ cm and $h_4=-1500$ cm therefore, when soil moisture is limiting, equation (1.11) becomes:

$$S(\psi,z)=\frac{2T_j}{z_{rj}}\alpha(\psi)\left(1-\frac{z}{z_{rj}}\right) \tag{1.12}$$

Equation (1.11) represents the distribution of transpiration in radial direction across the root zone. The equation for water uptake for two-dimensional axi-symmetry can be produced by substituting equation (1.11) into equation (1.12) to give:

$$S(\psi,z,r)=\frac{4T}{z_{rj}r_{rj}}\alpha(\psi)\left(1-\frac{z}{z_{rj}}\right)\left(1-\frac{r}{r_{rj}}\right) \tag{1.13}$$

In the first instance, this model will be applied to simulate water-uptake near established trees. Therefore under these circumstances, it is assumed that the root growth is not important and negligible in this work. Thus, dropping the subscript j for root growth, equation (1.13) then becomes:

$$S(\psi,z,r)=\frac{4T}{z_rr_r}\alpha(\psi)\left(1-\frac{z}{z_r}\right)\left(1-\frac{r}{r_r}\right) \tag{1.14}$$

This equation permits a simple linear distribution of the total transpiration (T) with both depth and radial distance from the tree. This equation (1.14) can also be re-cast and applied to a standard two-dimensional (x-z) domain.

The actual transpiration from a single tree, linearly over a root zone can be simplified as;

$$T = \int_0^{z_r} \int_0^{r_r} S(\psi, z, r)\, \partial r\, \partial z \tag{1.15}$$

Equation (1.11) is applied in a similar manner to equation (1.12) to evaluate the proportion of T_j extracted with depth. The distribution of the total transpiration from a single tree, linearly over a maximum radial root spread (r_j) is clearly a first approximation. The performance of this model is explored later in this chapter.

Equation (1.14) defines a sink term that can be implemented in equation (1.1) given that;

$$C(\psi)\frac{\partial \psi}{\partial t} = \frac{\partial}{\partial r}\left[K(\psi)\frac{\partial \psi}{\partial r}\right] + \frac{\partial}{\partial z}\left[K(\psi)\frac{\partial \psi}{\partial z}\right] + \frac{\partial K(\psi)}{\partial z} + \frac{1}{r}K(\psi)\frac{\partial \psi}{\partial r} - S(\psi, r, z) \tag{1.16}$$

Equation (1.16) therefore describes two-dimensional axi-symmetric moisture transfer in an unsaturated zone. Evaluation of the sink term via application of equation (1.14) provides a mechanism for distributing the extracted value of water over the root zone.

3. Results and discussion

This section discusses the findings of this research. All results obtained will further analyse and discussed.

3.1. Soil suction pattern

Fig. 3, Fig. 4 and Fig. 5 show progressive soil drying (high matric suction) events in the proximity of 1 m, 2 m and 4 m distances, respectively (Slope Station 1, Slope Station 2 and Slope Station 3, respectively) to an *Acacia Mangium* tree. There are several specific ranges of dry period dated 22nd July 2011 to 2nd August 2011, 4th February 2012 to 15th February 2012 and 20th July 2012 to 11th August 2012 that have been presented. These field monitoring data were only available at a limited range of date to represent the condition of minimum matric suction value (wettest) and the condition of maximum matric suction value (driest). The overall extent of the drying patterns period was between the wettest profiles on 22nd July 2011, 4th February 2012 and 20th July 2012, respectively (tip without shaded) and the driest profiles on 2nd August 2011, 15th February 2012 and 11th August 2012, respectively (tip with shaded). These profiles present little changes in matric suction below the depth of 1.5 m because the soil has reached limited values of root activity.

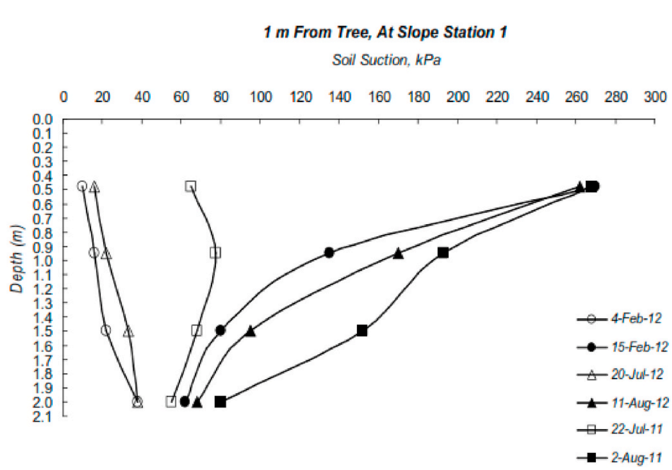


Fig. 3. Progressive development of matric suction during the drying periods at 1 m from tree.

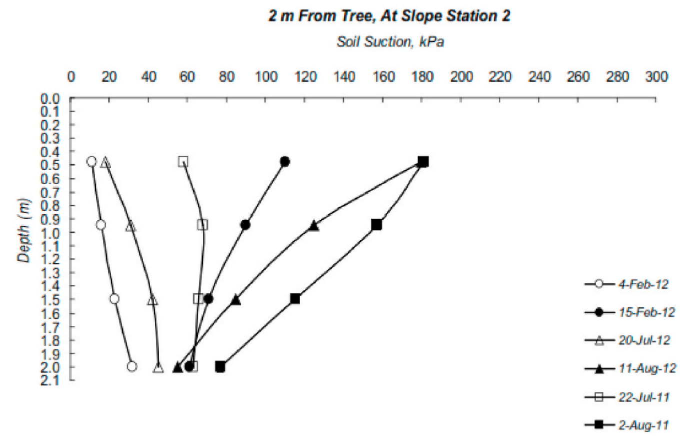


Fig. 4. Progressive development of matric suction during the drying periods at 2 m from tree.

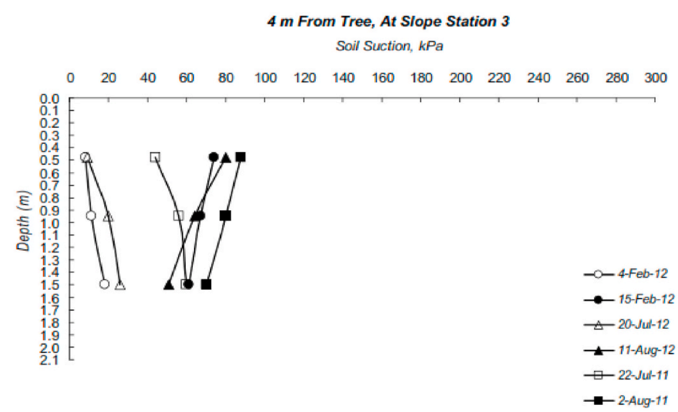


Fig. 5. Progressive development of matric suction during the drying periods at 4 m from tree.

Several almost similar soil drying pattern were encountered during this study. Figs. 3, 4 and 5 shows the driest profiles during the month of August for two consecutive years (2011 and 2012). By comparison, the drying pattern on 15th February 2012 produced less drying pattern value to 2nd August 2011 and 11th August 2012 (produced higher matric suction pattern value), although the overall drying pattern presented here remained essentially similar.

3.2. Soil-water characteristic curve

Fig. 6 shows the comparisons of the predicted failure envelope and experimental results for the sandy SILT soil at Faculty of Electrical Engineering. By adopting κ equal to 1.0 for the soil at study area, it was found that the predicted nonlinear failure envelope almost fit to the experimental data. This evidence proves that the nonlinear failure envelope equation is capable to produce a good representation of the shear strength behaviour of the soil.

The study area at Faculty of Electrical Engineering can be interpreted as homogenous soil profiles containing a layer of sandy SILT tropical residual soil. The moisture flow model is set to default as a homogenous and an attempt to keep the model as simple as possible. This is recognised as a limitation of the following simulation. Therefore, to simplify the soil profile, parameters encountered in the laboratory test were adopted here. The applied parameter for the model requires specification of the SWCC (specific moisture capacity) and the hydraulic conductivity relationship of soil at Faculty of Electrical Engineering for sandy SILT. Hydraulic properties of sandy SILT for the values of θ_r and θ_s

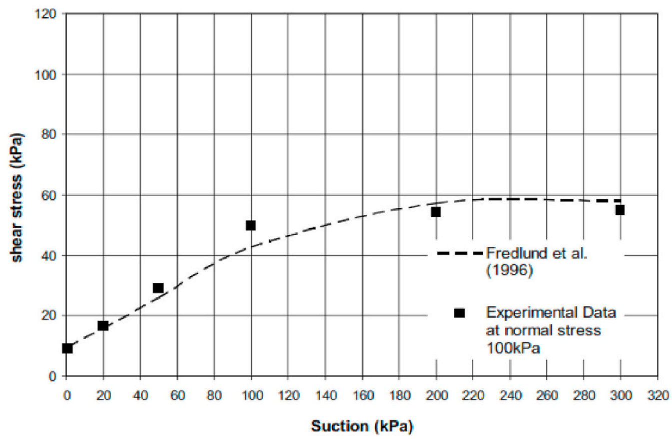


Fig. 6. Comparison of nonlinear failure envelope for the soil at study area.

have been taken directly from the measured moisture profiles presented in Fig. 7 and Table 1.

The saturated hydraulic conductivity, k_{sat} for sandy SILT at Faculty of Electrical Engineering based on laboratory results data presented as shown in Table 2. In this study, the saturated hydraulic conductivities, k_{sat} obtained from the laboratory tests were used to predict the hydraulic conductivity functions of unsaturated soils using Van Genuchten's (1980) method as shown in Figs. 8 and 9.

To simulate the approximately similar conditions of transpiration, research in this tropical region was selected to replicate the rate of transpiration at Faculty of Electrical Engineering. Research by Cienciala et al. (2000) of *Acacia mangium* mature tree in Malaysian region with a typical transpiration rate of approximately 5 mm/day was selected. This value has been used to trigger the transpiration rate engaged in this simulation. The information as in Table 3 would reveal the suggested 5 mm/day is within the range of previous researcher data. This value was distributed throughout the root tree zone via application of the water-uptake model.

In this part, the results of numerical simulation conducted on typical slope geometry model with tree at toe of Faculty of Electrical Engineering of induced transpiration in tropical residual soils were presented. The simulation matric suction distributions generated by tree water uptake numerical model were verified with those of field monitoring measurements (refer to Fig. 9). This monitoring result profiles was identified for adequate approach to be fitted with simulation result profiles. Comparisons have been made on matric suction, particularly at Station Slope to point out the validity of the value of the drying pattern.

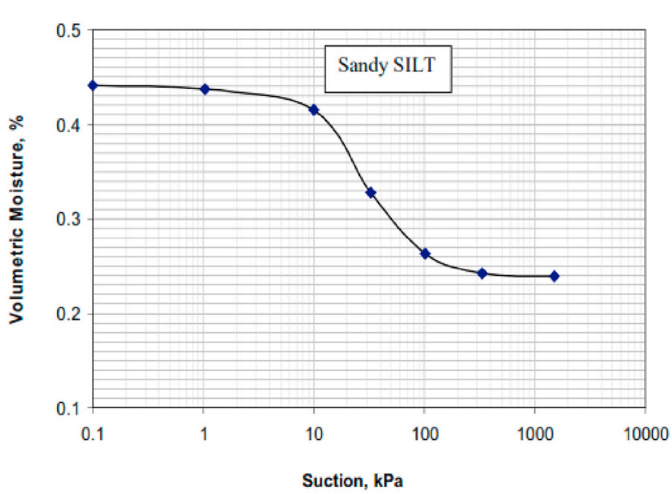


Fig. 7. The soil-water characteristic curves (SWCC) of the residual soil.

Table 1
SWCC parameters of the residual soils.

SWCC Parameter	sandy SILT
Saturated Vol. Water Content	0.44
Air Entry Value, A_{ev} (kPa)	10
Residual Water Content, θ_r	0.24
Minimum Suction at residual Water Content, ψ_{min} (kPa)	70

Table 2
Engineering properties of residual soil from within Singapore-Johor Bahru-Kulai area.

Researchers	Location	K_{sat} (m/s)
Author	UTM, JB	4.1 x 10^{-7}
Poh et al. (1985)	Singapore	1 x 10^{-8}
Marto et al. (2002)	Sedenak	0.48 x 10^{-8}
Marto et al. (2002)	Mutiara Rini, Skudai	1.34 x 10^{-8}
Ahmad (2004)	UTM, JB	3.6 x 10^{-8}
Kassim (2011)	UTM, JB	5.0 x 10^{-7}

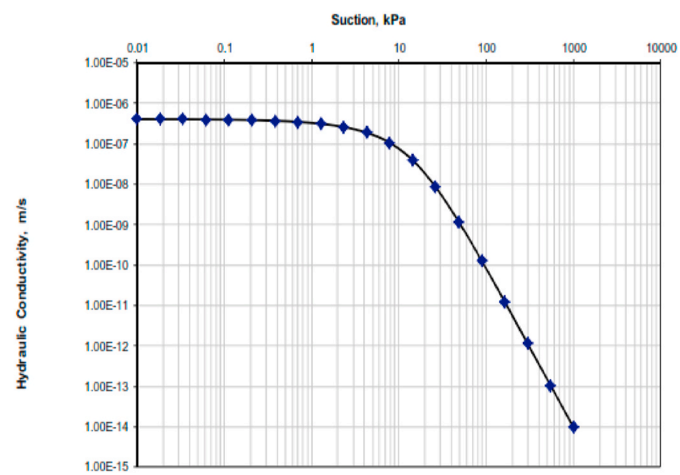


Fig. 8. Hydraulic conductivity function with responds to matric suction of the residual. soils predicted by using Van Genutchen's model (1980).

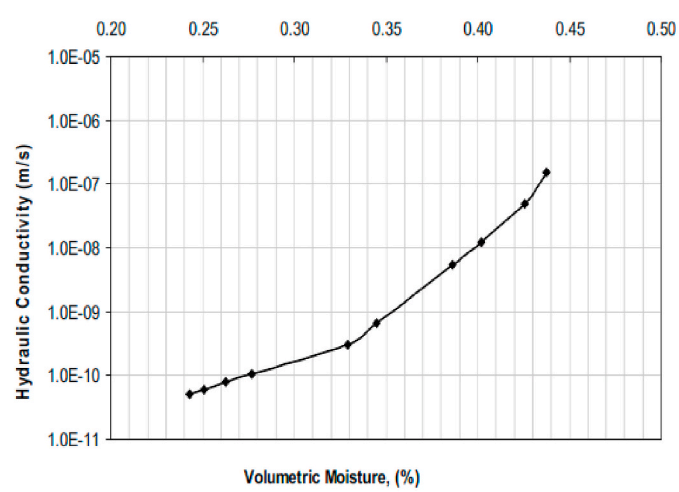


Fig. 9. Hydraulic conductivity function with responds to volumetric water content of the residual soils predicted by using Van Genutchen's model (1980).

Table 3
Transpiration rate of trees.

Authors	Type of Tree	Rate (mm/d)
Nisbet (2005)	Broadleaves	2
Indraratna et al. (2006)	Lime	3
Greenway (1987)	Acacia mollissima	3.5
Cienciala et al. (2000)	Acacia Mangium	4.6
Vrught et al. (2001)	Almond	4
Biddle (1998)	Common	5

3.3. *Verification of field monitoring results with numerical simulation*

The initial conditions employed in numerical simulation were based on the average value of lowest measured matric suction after rainfall. The simulation of tree water uptake was covered during the drying period condition of 21 day without rainfall event (20th July 2012 to 11th August 2012) during one and half year field measurement. The drying phase presented here was via the application of the transpiration rate as described above.

The formulating produced by Ali (2007) is believed to be the moisture flow equation without any deformation employed that may rise when moisture content are extracted from the soil. For the ease of discussion and to facilitate direct comparison between simulation and actual field measured data, the simulation results have been presented in matric suction (kPa).

Fig. 10, Fig. 11 and Fig. 12 show the comparison between the numerical simulation and field measurements results of the soil matric suction at maximum depth of 2.5 m at different distances (1.0 m, 2.0 m and 4.0 m) from the tree trunk. The simulation results profile shows that the maximum change in soil matric suction occurs at 0.25 m depth, which is located the maximum of root density at shallower depth of 0.5 m and to radial extent up to 4 m distance from the tree.

The results of simulation and field monitoring presented in Figs. 10, Figs. 11 and 12 were applied to mesh of slope model (Fig. 13). Both matric suction contours were presented in Fig. 14. These figures show a comparison between simulated and field measurement for matric suction contour. The maximum matric suction of 262 kPa was generated near the base of tree at toe of slope.

It indicated that the results from the simulation are in acceptable agreement with the field measurement results. It is a considerable importance to note that several of the differences between simulated numerical and field measurement are related to the inconsistence effect of root density. In short, in numerical model, root water uptake as a sink term was considered in flow moisture equation but the effect of root was not considered individually. It was found that the two set of results differ

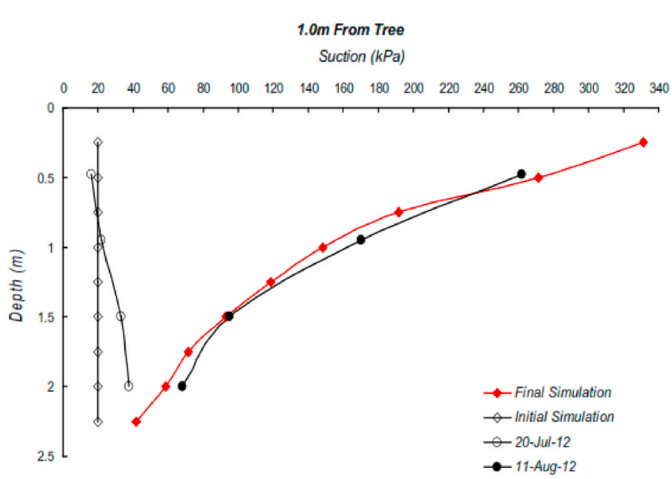


Fig. 10. Simulated (period of time 21 days) and measured matric suction profile. From 20th July 2012 to 11 th August 2012 at 1 m from tree.

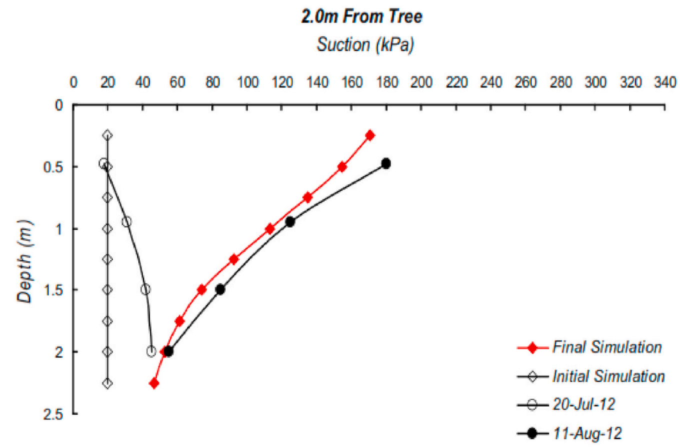


Fig. 11. Simulated (period of time 21 days) and measured matric suction profile. From 20th July 2012 to 11 th August 2012 at 2 m from tree.

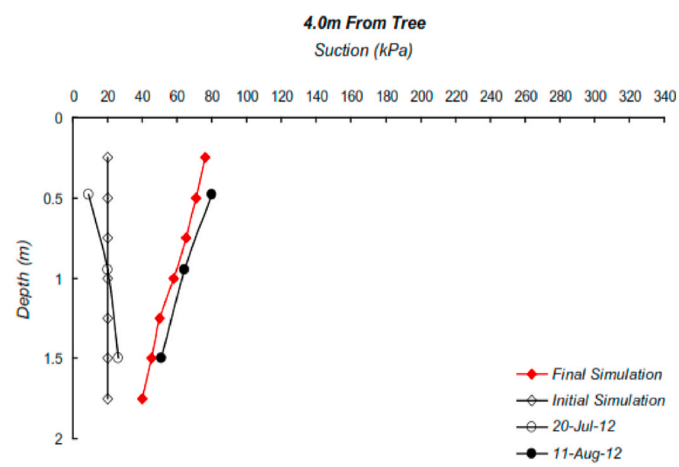


Fig. 12. Simulated (period of time 21 days) and measured matric suction profile. From 20th July 2012 to 11 th August 2012 at 4 m from tree.

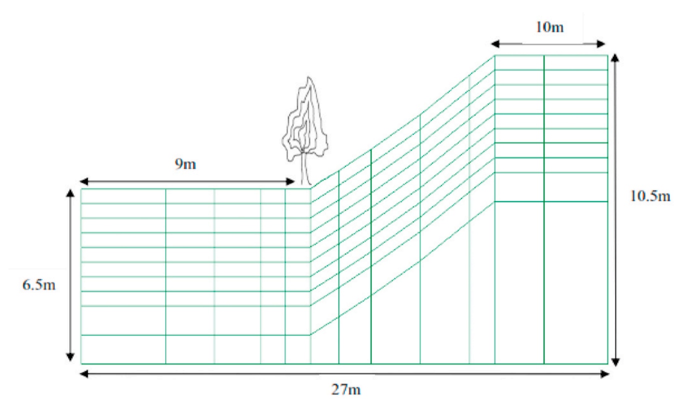


Fig. 13. Finite element mest of measured slope geometry with tree at toe of slope.

with each other, generally less than 5%.

4. Conclusion

The actual matric suction data obtained from the field monitoring yield reasonably within those determined from the analysis of SWCC. The experimental results were compared to the non-linear failure

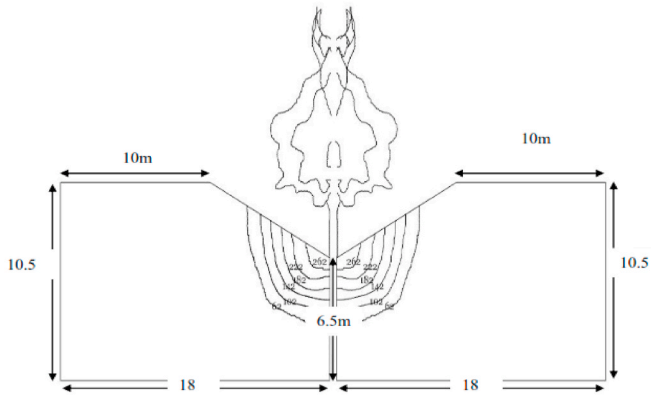


Fig. 14. Comparison of matric suction contour (kPa) generated within the vicinity of *Acacia Mangium* tree at toe of slope (a) numerical simulation. (b) actual field measurement results.

envelopes proposed by Fredlund et al. (1996). The predicted failure envelope and experimental results for the sandy SILT soil showed good agreement with the proposed failure envelope. The fitting parameter κ equal to 1.0 was adopted in dealing with the residual soil of sandy material.

The numerical modelling conducted to simulate the matric suction distributions generated by tree at toe of slope of the actual soil slope was presented in this chapter. The results were compared to the actual field measurements matric suction. In the present work, the approach adopted radial symmetry and a linear distribution of matric suction generated within both depth and radius. The simulation results of tree water uptake were chosen to cover during drying period in the field monitoring. The simulation matric suction profiles were presented at the same location of the field monitoring instruments. Majority of the matric suction were generated near the surface and significantly reduced with an increase in depth and distance from the tree.

The simulation numerical results have been directly compared with selected field measurements results. A good overall correlation between field matric suction profiles and simulated matric suction profiles has been achieved. Simulated numerical contour of matric suction generated by transpiration of tree at toe of slope has been presented. A comparison between simulation numerical and field measurement contour of matric suction at the slope of study area is inacceptable agreement. These works have been done to serve as a verification of the matric suction data collected from field measurement.

CRediT authorship contribution statement

M.F. Ishak: Conceptualization, Methodology, Software, Formal analysis, Writing - original draft. **M.F. Zolkepli:** Writing - original draft, Proofread, Paper Organization, Original draft preparation. **M.Y.M. Yunus:** Visualization, Investigation. **N. Ali:** Supervision, Validation. **A. Kassim:** Supervision, Validation. **M.S.I. Zaini:** Writing - review & editing.

Declaration of competing 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pce.2021.102980.

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