

TREE WATER UPTAKE ON SUCTION DISTRIBUTION IN UNSATURATED  
TROPICAL RESIDUAL SOIL SLOPE

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**In the name of ALLAH, the almighty and most merciful.**

To my beloved family

Nazirah Bte Brahim

Nurfarizah

Muhammad Afiq

Hj Brahim Bin Bujang

Hjh Ramlah Bte Hasan

In memory of Hj Ishak Bin Mohd Amin and Hjh Munah Bte Ahmad

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## ABSTRACT

This study provides an investigation of active root tree zone located at the toe of a slope. This section and its vicinity generated matric suction due to tree water uptake on tropical residual soil slope. The research employed several approaches i.e field monitoring, laboratory experimental and numerical modelling. A field monitoring was carried out to collect matric suction data at the slope with two conditions; in absence of a tree and with a tree located at the toe of a slope. The unsaturated shear strength behaviour of soil under different stress level is investigated, using uncomplicated testing procedure subject to actual matric suction encountered during field monitoring. The numerical simulation modelling was applied based on the laboratory results to obtain the most appropriate condition to replicate the tree water uptake within the soil slope. A decrease in matric suction occurred after a long duration of intense rainfall. This condition was function as an initial condition before the water uptake driven by active root tree generated to the maximum matric suction (low moisture content). The pattern of matric suction profiles revealed that majority of matric suction changes was greater at the proximity of tree trunk below 4 m and at a shallow depth of 0.5 m. Transpiration on single mature tree has significantly altered the matric suction or moisture variation distribution on an unsaturated soil slope. This study also illustrated the nonlinear relationship between the apparent shear strength and suction influencing the stability of the slope. The assessment of slope stability due to the influence of a tree induced suction was provided in this research. The factor of safety against slope failure has improved up to 63 % on slope with tree at toe compared to a slope without tree. Lastly, the numerical simulation modelling of matric suction induced by a tree has been verified through comparison to actual field monitoring results recorded during the dry period. Generally, an acceptable agreement between simulation and field monitoring results has been achieved. This research delivers a strong belief that a preserved mature tree can improve soil properties in slopes designs.

## ABSTRAK

Kajian ini merangkumi penyiasatan di zon aktif akar pokok yang terletak di kaki cerun. Di bahagian ini dan kawasan sekitarnya menandakan sedutan matrik disebabkan pengambilan air daripada pokok di tanah tropika sisa pada sekitar cerun. Penyelidikan ini mengambil beberapa pendekatan iaitu pemantauan di lapangan, ujikaji-ujikaji makmal dan pemodelan berangka. Pemantauan di lapangan yang dijalankan bagi mengumpul data sedutan matrik di cerun dilakukan dalam dua keadaan; tanpa kewujudan pokok dan dengan kewujudan pokok yang terletak di kaki cerun. Sifat kekuatan ricih tanah tak tepu diuji dibawah tahap tekanan yang berbeza dengan menggunakan kaedah yang tidak rumit bergantung kepada nilai sebenar sedutan matrik yang direkodkan semasa pemantauan di lapangan. Simulasi berangka dijalankan berdasarkan keputusan makmal untuk mendapatkan nilai yang paling sesuai bagi menunjukkan pengambilan air daripada pokok di cerun tanah dengan corak sedutan matrik di lapangan. Penurunan sedutan matrik berlaku selepas hujan lebat yang panjang. Situasi ini berfungsi sebagai keadaan awalan sebelum pengambilan air didorong oleh akar pokok yang aktif menjana sedutan matrik kepada nilai yang paling tinggi (kandungan kelembapan yang rendah). Corak profil sedutan matrik mendedahkan bahawa kebanyakan perubahan sedutan matrik adalah lebih besar berdekatan batang pokok berdekatan (4 m) dan pada kedalaman yang cetek (0.5 m). Transpirasi hanya daripada sebatang pokok matang dapat memberikan sumbangan yang amat ketara dalam mengubah sedutan matrik atau kelembapan pada cerun tanah tak tepu. Terdapat hubungan tak linear di antara kekuatan ricih dan sedutan yang mempengaruhi kestabilan cerun. Penilaian kestabilan cerun disebabkan pengaruh sedutan oleh pokok juga terdapat dalam kajian ini. Faktor keselamatan terhadap kegagalan cerun telah bertambah sehingga 63 % pada cerun dengan pokok di kaki berbanding dengan cerun tanpa pokok. Terakhir sekali, simulasi pemodelan berangka sedutan matrik yang dijanakan oleh pokok dan disahkan secara langsung dengan keputusan pemantauan sebenar yang dicatatkan semasa tempoh keadaan kering. Secara amnya, keputusan simulasi dan pemantauan di lapangan menunjukkan hubungan yang munasabah. Kajian ini memberikan keyakinan yang kuat terhadap pemeliharaan pokok matang yang boleh memperbaiki sifat-sifat tanah dalam merekabentuk cerun..

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## LIST OF SYMBOLS

$A_{ev}$	-	Air entry value
$c'$	-	Effective cohesion
$e$	-	Void ratio
$g$	-	Gravity = 9.81 m/s <sup>2</sup>
$G_s$	-	Specific gravity
$I$	-	Rainfall intensity
$k$	-	Water coefficient of permeability
$k_{sat}$	-	Saturated permeability
$K(\psi)$	-	Hydraulic conductivity of wetted zone
$L_f$	-	Wetting front depth
$L_r$	-	Redistribution depth
$m_w$	-	Slope of soil water characteristic curve (SWCC)
$n$	-	Porosity
$q$	-	Rainfall unit flux
$t$	-	Time
$u_a$	-	Pore-air pressure
$u_w$	-	Pore-water pressure
$(u_a - u_w)$	-	Matric suction
$W$	-	Total weight of soil
$W_{ev}$	-	Water entry value

$\beta$	-	Slope inclination angle
$\chi$	-	Parameter related to the soil degree of saturation
$\phi'$	-	Effective friction angle
$\phi^b$	-	Angle indicating unsaturated
$\gamma_d$	-	Unit weight of dry soil
$\gamma_w$	-	Unit weight of water = 9.81 kN/m <sup>3</sup>
$\pi$	-	Osmotic suction
$\theta$	-	Volumetric water content
$\theta_i$	-	Initial volumetric water content
$\theta_r$	-	Residual volumetric water content
$\theta_s$	-	Volumetric water content at saturation of absorption curve
$\rho_b$	-	Bulk density
$\rho_d$	-	Dry density
$\rho_w$	-	Density of water
$\sigma$	-	Total normal stress
$\sigma'$	-	Effective normal stress
$\tau_f$	-	Shear stress at failure
$\psi$	-	Suction
$\psi_{min}$	-	Minimum Suction value
$\psi_T$	-	Total suction
$C(\psi)$	-	Specific moisture capacity (cm <sup>-1</sup> )
$r_r$	-	Maximum rooting radial (cm)
$S_m$	-	Shear force mobilized on the base of each slice (kN)
$S(\psi, z, r)$	-	Sink term (cm <sup>3</sup> /cm <sup>3</sup> /s)
$T, T_j$	-	Potential Transpiration rate



$z_r$	-	Maximum rooting depth (m)
$\alpha(\psi)$	-	Pressure head dependent reduction factor
$N$	-	Total force on the base of the slice (kN)
$O$	-	The centre of slip rotation
$\Theta$	-	Normalized volumetric water content
$\chi$	-	Parameter related to the soil degree of saturation
$C_{app}$	-	Apparent shear strength
$q_u$	-	Undrained compressive strength
$W_s$	-	Weight of solid soils in the specimen
$W_T$	-	Target weight of the specimen
$W_w$	-	Weight of water in the specimen
$(\Delta\sigma_d)_f$	-	Deviator stress at failure
$\varepsilon$	-	Axial strain
$\omega$	-	Moisture content
$\omega_0$	-	Initial moisture content
$\omega_T$	-	Target moisture content of the specimen

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## CHAPTER 1

### INTRODUCTION

#### 1.1 Background of the Study

In recent years, rapid urbanisation, overdevelopment and deforestation have contributed further to the destabilising of soil and soil surrounding it, with a greater number of developments contributed to gradually weaken the earth structure. As a consequence, some of catastrophic slope failure events occurred in Malaysia due to the removal of mature trees at the toe of slopes. One of the events took place at Hidayah Madrasah Al-Taqwa orphanage at km 14 Jalan Hulu Langat, Selangor. This tragedy occurred during a long spell of daily torrential rainfall event which suddenly triggered the landslide, wrecked the houses and killing 16 orphans. Further investigation of the surrounding area revealed that cutting down trees at the toe of a slope lead to this disaster (Jamaluddin *et al.*, 2011).

Several case studies have shown that slope failures may have attributed to the clearing of trees that vanishes the reinforcement provided by roots to the soil (Wu, 1995; Hunt, 2007; Jamaluddin *et al.*, 2011). Slope failures commonly occur when the shear strength of the soil is reduced through a decrease in effective stress due to pore water pressure increment (Glendinning *et al.*, 2009). This may happen due to climate change and antecedent rainfall, which can be found mostly in Malaysia. In fact, sudden

increase in porewater pressure can cause sudden weakening of the soil strength and lead to slope failure. Therefore, it is significantly important to find an economically and eco-friendly solution on how to minimise the risk and bring sustainability to the slopes. This study considers the vegetation approach in maintaining and enhancing soil strength through moisture content reduction in minimising the risk of slope failure.

Vegetation prevents collapse by reducing water pressure (increasing suction through water uptake) due to suction produced by vegetation and acts to stabilise the slopes by increasing effective stress, thus leading to an increase in soil shear strength. Simon and Collison (2002) claimed hydrological effect as an important key finding as mechanical effect, which it increases FOS up to 70%. It should also be noted that if trees are cut down it may result in failure when pore water pressures are recovered because strain softening has already occurred (due to previous seasonal cyclic loading effects). This is important in the management of vegetation and engineers must be wary of felling trees without first understanding the hydrology condition.

It is acknowledged that vegetation has various mechanical and hydrological effects on ground stability. Many researchers (Greenway, 1987; Greenwood, 2006; Genet et al., 2010; Schwarz et al., 2010; Ali, 2010) have attempted to quantify the focusing on the mechanical strengthening provided by the roots, while ignoring the implications of evapotranspiration on the soil pore water pressure. However, a model has been developed; an application of a numerical model of water uptake in the vicinity of established trees produced by Fatahi et al., (2010). They development of the mathematical model for the rate of root water uptake considers ground conditions which highlighted the inter-related parameter of contribution to the development of conceptual evapotranspiration and root moisture uptake equilibrium model.

The water-uptake numerical model was also provided by Ali and Rees (2008) which marked a new approach on hydrological effect for the stability of slope. They used a numerical model to develop a distribution soil moisture content profile to simulate the tree water-uptake. The sink term (extraction) was only applied within the pre-defined geometry of the root zone. However, moisture was still free to migrate towards this zone and simulated contours in terms of capillary potential after drying and heavy rainfall event.

The study conducted by Biddle (1998) on lime tree found that the active root zone has extended until 2 m depth with a radial of 5 m for both left and right direction. He also concluded that the pattern of soil moisture deficit contour has been affected by the soil moisture transfer from various species of trees. He discovered significant changes in soil moisture contour due to the different type of trees, regardless of the soil types. It was found that the pattern of soil moisture deficit has occurred and this may similar for different clay and the amount of clay shrinkage with the associated risk of structural damage depends on the clay characteristics. In tropical country such as Malaysia, the tropical monsoon rainfall and particularly dry period can reflect patterns of soil moisture. This result and analysis can revealed the effect of tree by correlation with meteorological data.

Tree root can help to prevent landslides in two ways, either hydrological effects; modifying the soil moisture regime via evapotranspiration and providing root reinforcement within the soils. The first factor can be very important to prevent landslides and debris flow form occurring during an extensive rainy season, especially in the tropics and sub-tropics country where evapotranspiration is high throughout the year. This condition can also lead to deeper-seated landslides, such as earthflows due to high moisture contents after vegetation is removed (Sidle and Ochiai, 2006). However, Greenway (1987) has suggested that it is possible to develop a model, which can indentify the relationship between transpiration to soil moisture content used in slope analysis. A model of this approach would be able to determine major influence of transpiration driven by tree integrated with slope stability.

This study explores the active root zone of a tree that lies at the toe of the slope and the matric suction generated within this section of the slope. The aim of the research was to investigate the pattern of matric suction distribution at slope in response to tree water uptake. In relation to that, the significant matric suction changes can be relative to the behaviour of strength envelope in unsaturated tropical residual soil. The research was further extended by applying the changes of matric suction to the geotechnical slope stability problem as discussed below.

In this study, conditions such as the ground water table is deep enough and tree root activity is above ground water table that tree induced suction influence matric suction on soil. In this case, it is appropriate to perform slope stability analyses which include the shear strength contribution from the matric suction. A modified form of the Mohr-Coulomb equation can be used to link shear strength to soil matric suction. Theory of limit equilibrium of forces and moments used to compute the FOS (Factor of Safety) against failure. The limit equilibrium method of slices is widely used for its simplicity particularly when compared to the finite element method (Fredlund and Rahardjo, 1993, Renaud et al., 2003). The FOS is defined as that factor by which the shear strength of the soil must be reduced in order to bring the mass of soil into a state of limiting equilibrium along a selected critical slip surface.

## **1.2 Problem Statement**

Many hill slope areas in Malaysia, both engineered slope and natural slope are particularly vulnerable to soil erosion, shallow landslides and the most catastrophic disaster are mass slope failures. Slope failures mostly occur during intense increase of soil moisture and porewater pressure due to antecedent and prolonged rainfall. The increasing soil moisture or pore water pressure can be seen as the main contributing factor for decreasing soil shear strength thus leading to the weakening of the slope stability, resulting in FOS reduction.

Many researchers (Thorne, 1990; Ali, 2010; Schmidt *et al.*, 2001; Normaniza *et al.*, 2007) have discovered the effect of mechanical on tree root that can benefit in preventing shallow slope failure but only a few studies to quantify the hydrological effect for the potential benefit stabilization of slope. Apart from providing natural mechanical soil reinforcement, tree roots dissipate excess pore water pressure and produce sufficient matric suction to increase the shear strength of the surrounding soil. The hydrological effect is related much closed to soil moisture variation and can be directed through transpiration. This effect is found to be important as mechanical effect provides significant increase in soil strength that will definitely improve slope stability in certain conditions. It must be considerate before cutting and felling down the trees without understanding the hydrological condition would have a great impact on the stabilization of slope and soil surrounding it.

### **1.3 Objectives Of Study**

The aim of this study is to explore the soil matric suction distribution due to tree induced suctions generated within the toe of the slope. The changes of matric suction were analysed to reveal the soil moisture profiles in the vicinity of a tree. These soil matric suction changes affect the stability of unsaturated slopes in the study area. To achieve this aim, several objectives of the study are stated below;

- I. To determine soil matric suction of a slope with mature tropical tree existing at the toe of the slope. This is accomplished through installations of equipments in the vicinity of tree with certain depths and distances to continuously measured matric suction for one and half year period.
- II. To establish profiles that demonstrate influence of tree water-uptake with through condition from prolonged antecedent rainfall to dry period. The changes

in matric suction data and suction profiles would be analyses to reveal the patterns in soil matric suction.

- III. To develop a matric suction contour (soil moisture) distribution to reveal the moisture deficit at active root tree zone. The distributions of matric suction were used to represent the profile of matric suction influenced by single mature tree at toe of slope.
- IV. To analyses the influence of tree induced suction on Factor of Safety (FOS) throughout this course of monitoring study.
- V. To verify field monitoring and laboratory results through comparison with established numerical models. A detailed numerical modelling was carried out to simulate suction distributions and failure envelop of tropical residual soil in the study area.

#### **1.4 Scope Of Study**

This study presents patterns of soil moisture transfer and migration due to the influence of tree root water-uptake on the unsaturated soil condition. It focuses on the hydrological aspect on soil moisture pattern within the vicinity of the tree. The mechanical aspect of the tree roots such as tensile strength that bond between root and soils which can lead to increasing soil strength are not consider in this study.

The current work would consider the effect of single tropical mature tree such as *Acacia mangium* at the toe of the slope with the determination of root zone patterns limited to a depth less than 2 m and radius distance not more than 5 m. The root growth will be excluded in this work scope and only consider on transpiration by tree. The



study also presented assessment the stability of typical geometry cut slope constructed 13 years ago at Faculty of Electrical Engineering, University Teknologi Malaysia. The approach to encounter soil matric suction profiles was based on field instrumentations monitoring and laboratory works.

Nevertheless, the focus on aspect of this study is limited to the influence of suction than changes on shear strength by using the extended Mohr-Coulumb equation (Fredlund *et al.*, 1978). The water-uptake consideration in this study only represents the soil near-saturated conditions until the drying period due to transpiration of tree by not considering the hysteresis effect. The calculations of FOS presented here only consider the magnitude of matric suction variation driven by transpiration only.

A series of condition during field monitoring works were analysed with the results in the laboratory. Apart from that, the field monitoring and laboratory result brought significant input parameters to apply in the numerical model and the stability analysis of slopes. To verify the numerical model, a parametric study has been conducted by considering conditions that could be incorporated in the field monitoring results. The comparison of these works revealed that tree moisture transfer or induce suction is beneficial in maintaining stability of unsaturated soil slopes.

### **1.5 Significance Of Study**

The exploration of this research may be viewed as comprehensive or/and an alternative to the existing field monitoring and modification laboratory testing program for tropical residual soils. The benefits that would be gained from the study may include the followings:

- I. Providing essential quantification information on the behaviour of matric suction (pore-water pressure) changes in relation to tree water up taken with measurable rainfall and soil parameters change with matric suction in assessing the stability of unsaturated residual soil slopes.

- II. Representing hydrological condition in viewing the significant contribution of a single mature tree in altering the matric suction or moisture content variation distribution driven by transpiration on unsaturated soil slopes.

## 1.6 Thesis Organization

This thesis consists of eight (8) chapters; *Introduction* (Chapter 1), *Literature Review* (Chapter 2), *Research Methodology* (Chapter 3), *Preliminary Data* (Chapter 4), *Effect Of Tree Water Uptake On Suction Distribution Pattern* (Chapter 5), *Analysis Of Tree Induced Suction On Slope Stability* (Chapter 6), *Tree Induced Suction And Numerical Modelling* (Chapter 7) And *Conclusions And Recommendations* (Chapter 8). At the end of each chapter excluded Chapter 8, concluding remarks were provided to briefly summarize the content of the chapter.

As introduction to generally describe the background of problem related to slope failure associated with clearing of trees is the main discussion in Chapter 1. Apart from this problem statement, Chapter 1 also discusses the objectives, scopes and significance of the present study. The brief description on tree can improve slope stability from various effects of mechanical and hydrological are presented. Vegetation may prevent collapse by reducing water pressure as an economically and eco-friendly solution was also presented.

The related research work and review of literature is presented in Chapter 2. This chapter provides descriptions and concepts of appropriate theories published in literature pertaining on analysis of tree water uptake in unsaturated soil. In addition, Chapter 2 also outlines methodologies of the laboratory techniques, field monitoring work and numerical model that employed in the previous studies.

Research methodology particularly laboratory experiments and field monitoring are described detail in this study is explained in Chapter 3. One of the objectives is to collect basic data at study area. In Chapter 3 also describes the detail of the equipment and procedures to recorded and measured field and laboratory work.

The discussions on the following chapters in this thesis are related to the results and analyses, i.e. Chapter 4, Chapter 5 and Chapter 6. Chapter 4 presents and discusses the preliminary data obtained from two main components of experimental results and field monitoring data as described in Chapter 3. The results include the characterization of residual soil and the response of matric suction distribution particularly influence by tree water uptake through out field observation.

The discussion related to hydrological effect on unsaturated slope is presented in Chapter 5. The analyses are mainly focuses on the field monitoring results influence by tree water uptake. This revealed a contribution of single mature tree can be significant alter the suction or moisture variation distribution driven by transpiration on unsaturated soil slope.

Chapter 6 is considering on how matric suction generated by tree can be influence for an assessment of the stability on unsaturated soil slope. The typical of engineered slope geometry and behaviour of soil shear strength related to matric suction effects the Factor of Safety (FOS) against failure are examined. The FOS was presented with corresponding variation of actual matric suction of slope with tree at toe and slope without tree are consider.

Chapter 7 presents the exploration of the numerical model of moisture migration pattern in proximity of mature tree. The model is applied to simulated matric suction distribution and compared with field measurements that have been identified earlier in Chapter 4 and Chapter 5. The model serves to generate the matric suction by tree at toe of slope that influences the overall hydrological condition of the slope.

The final chapter of the thesis (Chapter 8) covers the overall conclusions of the thesis drawn from the present study and the recommendations for further researches.

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