SOIL SUCTION MODEL FOR GRASS EVAPOTRANSPIRATION

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I dedicate this project to Almighty God my creator, my source of wisdom, inspiration, knowledge and understanding. He has been the source of my strength throughout this program and on His wings only have I soared. I also dedicate this work to my mother, Cecilia Chin who has encouraged me all the way as my first and lifetime teacher. To my father, Joseph Ong for supporting and encouraging me to ensure that I give it all it takes to finish that what I have started. To my friends and my teachers especially my supervisor Assoc. Prof. Dr. Nazri Ali who gives me full guidance and support. Thank you. My love for you all can never be quantified. God bless you.

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ABSTRACT

This study investigated the soil matric suction distribution in a field covered by grass Axonopus Compressus and free from the effect of the tree. The research employed several approaches such as field monitoring, laboratory experimental, model proposal, coding program and slope stability. A field monitoring program was carried out from August to December 2015 to collect the data of matric suction by jet-filled tensiometer, accounting for less than 10 times of continuous drying of longer than 5 days over 5 months of measurement. The suction profiles show that the variation was greater in the root zone (< 30 cm) and less effect in deeper depth. The grass field failed to retain the soil suction, which dropped to a minimum magnitude at all depths after some rainfall event. Besides, the rate of evapotranspiration of grass was investigated by measuring the daily total weight loss of grass samples. The water loss from soil continuously even on full cloud rainy day. Generally, the water lost from soil to air every day even during the rainy day with the lower evaporation of 0.4-0.9 mm/day. The rate of evapotranspiration could reach almost 8.0 mm/day and around 5-6 mm/day on normal sunny day. A mathematical equation was proposed as the suction model by considered rooting depth and evapotranspiration to estimate the suction profile of soil after specific drying period. Proposed suction model and some existing water uptake models have been coded into a program by MATLAB graphical user interface. The code in the program was verified with a set of test plan to ensure the program works as planned and designed. The suction model has been validated with the site measurement data. The shallow slope stability was analysed by program SLIP4EX in saturated and unsaturated conditions. The enhancement due to the influence of grass induced suction and root tensile strength were provided in this research. The factor of safety against slope failure has improved 0.6-4.8% at various depths when the effect of suction included. The comparison between the effect of induced suction and root tensile strength showed better enhancement from mechanical effect since suction was not high. The contribution of suction was not affected by changes of soil cohesion, however, the effect is higher when friction angle of soil is high and angle of slope is low. This research developed mathematical equation for soil water uptake to deliver a better understanding of grass suction distribution and effect to the slope stability.

ABSTRAK

Kajian ini membuat penyiasatan tentang pengedaran sedutan matrik tanah di kawasan lapang yang diliputi oleh rumput parit dan tidak dipengaruhi oleh pokok. Penyelidikan ini merangkumi beberapa pendekatan iaitu data pemantauan, ujikaji makmal, cadangan model, kod program dan kestabilan cerun. Pemantauan data di kawasan kajian dijalankan dari Ogos sehingga Disember 2015 untuk mengumpulkan data sedutan matrik degan menggunakan alat “jet-filled tensiometer”. Data yang dikumpul menunjukkan bahawa terdapat kurang daripada 10 tempoh pengeringan yang berterusan lebih daripada 5 hari sepanjang 5 bulan tersebut. Profil sedutan menunjukkan bahawa perubahan yang lebih besar di zon akar (< 30 cm) dan kesan sedutan berkurang di tahap yang lebih dalam. Kawasan kajian tersebut tidak berjaya mengekalkan sedutan tanah yang dijana setiap masa, ia mungkin menurun ke tahap minimum pada semua kedalaman pengukuran selepas hujan. Selain itu, kadar evapotranspirasi rumput telah dikaji dengan mengukur jumlah kehilangan air dalam sampel rumput setiap hari. Data menunjukkan air hilang dari tanah secara berterusan walaupun pada hari hujan yang dipenuhi dengan awan. Secara umum, air hilang dari tanah ke udara setiap hari walaupun semasa hari hujan dengan penyejatan yang lebih rendah iaitu 0.4-0.9 mm sehari. Kadar evapotranspirasi boleh mencapai sehingga 8.0 mm sehari dan 5-6 mm sehari pada hari yang biasa. Satu persamaan matematik telah dicadangkan untuk mensimulasikan corak sedutan matrik dalam tanah. Persamaan tersebut merangkumi kedalaman akar dan evapotranspirasi rumput. Ia berfungsi untuk menganggarkan profil sedutan tanah selepas tempoh pengeringan tertentu. Model sedutan yang dicadangkan dan beberapa model pengambilan air telah dikodkan ke dalam program dengan menggunakan MATLAB. Kod program ini telah disahkan dengan pelan ujian untuk memastikan program ini berfungsi seperti yang dirancang dan direka. Model sedutan telah disahkan dengan data corak sedutan yang dikumpul dari pengukuran di tapak. kestabilan cerun cetek dianalisis dengan menggunakan program SLIP4EX dalam keadaan tepu dan tidak tepu. Kajian ini menunjukkan pengaruh sedutan matrik dan kekuatan tegangan akar rumput ke atas peningkatan kekuatan tanah. Faktor keselamatan cerun bagi mengatasi keruntuhan telah meningkat sebanyak 0.6-4.8% di bebrapa tahap kedalaman tertentu kerana pengaruh sedutan. Perbandingan antara pengaruh sedutan matrik dan kekuatan tegangan akar menunjukkan peningkatan yang lebih tinggi atas bantuan mekanikal akar kerana sedutan matrik adalah rendah. Sumbangan daripada sedutan tidak dijejas oleh perubahan kelekatan tanah, tetapi kesannya adalah lebih tinggi apabila sudut geseran tanah adalah tinggi dan sudut cerun adalah rendah. Kajian ini telah menghasilkan satu persamaan matematik pengambilan air untuk menyampaikan pemahaman yang lebih teliti mengenai pengagihan corak sedutan rumput dan kesan ke atas kestabilan cerun.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

1D	-	1-dimensional
2D	-	2-dimensional
3D	-	3-dimensional
SLIP4EX	-	A program for routine slope stability analysis
ASTM	-	American Society for Testing and Materials
A	-	Area
AC	-	Axonopus Compressus
B	-	Bare
BS	-	British Standard
CD	-	Cynodon Dactylon
D	-	Depletion
ET	-	Evapotranspiration
FX	-	Fredlund & Xing
GPS	-	Global Positioning System
G	-	Grass
HA	-	Highway Agency
LAI	-	Leaf area index
LL	-	Liquid limit
O-R	-	Ojha & Rai
PL	-	Plastic limit
PI	-	Plasticity index
PT	-	Potential transpiration
RC	-	Relative compaction
RAI	-	Root area index
RLD	-	Root length density

SWCC	-	Soil water characteristic curve
dbh	-	Trunk diameter
UD	-	Undisturbed
USCS	-	Unified soil classification system
UK	-	United Kingdom
USA	-	United State of America
UTM	-	Universiti Teknologi Malaysia
VG	-	Van Genuchten
w.c.	-	Water content
WRC	-	Water retention curve

LIST OF SYMBOLS

S - Actual water uptake

c_v' - Additional cohesion

θ - Angle between direction of T and slip surface

u - Average water pressure

α - Base angle

c' - Cohesion

D - Depletion

z - Depth

T_{rd} - Design root force

K - Earth pressure coefficient

b - Empirical coefficient

F - Fraction of root length density

ϕ' - Friction angle

Δu_v - Increase in average pore water pressure

ΔU_{1v} - Increase in water force on left side of slice

ΔU_{2v} - Increase in water force on right side of slice

l - Length

W_v - Mass of vegetation

S_{max} - Maximum water extraction

n - Number of layer

F_r - Partial safety factor

n - Porosity

T_p - Potential transpiration

h - Pressure head

θ_r - Residual water content

L_r - Root length

z_r - Rooting depth

K_s - Saturated permeability

θ_s - Saturated water content

b - Slice width

α - Slope angle

α_a - Soil water availability

a_w - Soil water available factor

G_s - Specific gravity

ψ - Suction

T - Tensile root / reinforcement force

Δz - Thickness of layer

W - Total water extracted

T_{ru} - Ultimate root force

e - Void ratio

θ_w - Water content

U_1 - Water force on left side of slice

U_2 - Water force on right side of slice

β - Weighted stress index

β_w - Wind direction in angle

D_w - Wind force

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

Recently, the development and maintenance of construction starts to go green and more environmental in term of design, material, construction technology, as well as having more trees or plants. Tree has the function of reduce carbon dioxide, increasing suction, reduce water pressure, more aesthetic and prevent landslide but it could also very danger to the civil structure.

Trees have the power that can damage the building services direct or indirectly. Direct damage from tree can be avoided by refer to the safe distances guidance given in BS5837: 2005. Indirectly, tress can cause the clay soils to shrink by drawing the water along their roots. Shrinkage will results in vertical and horizontal ground movements and the amount of shrinkage depends on the type of clay soil, size of tree and also climate. In a typical year expansive soils cause a greater financial loss to property owners than earthquakes, floods, hurricanes and tornadoes combined (Nelson and Miller, 1992).

According to Jones and Jefferson (2012), shrinkage and swelling of clay soil due to trees can cause the foundation movements that could damage the buildings. This is a serious problem that needs to take into consideration. The prediction of heave shrinkage should make through the changes in soil moisture content. The soil suction is a limiting parameter for free water uptake and also nutrient uptake. The relationship of plant root system and soil water play an important role in agricultural science and geotechnical engineering. So, the variation in soil suction that occurs in presence or absence of plant is very important for an analysis. In addition, the different of moisture content could change the physical or mechanical properties of soil (Artyunov *et al*., 1985). On top of that, soil moisture content also influence the deformation behaviour within root-reinforced soils when subjected to shear (Fan & Su, 2009). Therefore, a study on changes of moisture content in soil is required to understand some geotechnical and geo-environmental analysis.

Other than trees, the plenty available grasses would also lead to green environment and possible to enhance the soil properties. The contribution of plant root systems on slope stability and erosion control has received great attention in recent years. Plant roots are believed could greatly increase slope stability and control erosion (Abe and Ziemer, 1991; Coutts, 1983; Gray and sotir, 1996; Gyssels *et al*., 2005; Waldron, 1977; Wu *et al*., 1979; Gray 2009). Roots of grass are short but bind the upper layer of soil and reduce the rainwater infiltration into the upper layer of loose soil (Huat *et al*., 2006). Meanwhile, roots of large plant (stitching material) increase the shear strength of rock mass generally. However, trees take times to grow although its contribute lots on reinforcement (Rai and Shrivasta, 2012). In general, fine roots are shown a better contribution on soil fixation compare to coarse roots. According to Gyssels *et al*. (2005), shallow and dense root network of fine roots is most effective in water erosion processes control. However, fine roots are not good in tension or bending as coarse roots can resist both of it (Bischetti *et al*., 2005). A combination of deep roots and shallow rooted grass could anchoring and stabilise the topsoil then strengthening the slope (Hairiah *et al*., 2006). Even though the relative importance of roots characteristics may be limited, the recent development makes the effort of further detailed investigation worth. So effect of root system will be appreciated and concerning selected species for land rehabilitation (Reubens *et al*., 2007).

This study explores the water uptake and matric suction produced by the roots of grasses in selected research plot which covered by grasses and free from effect of tree. The aim of the research is to investigate the matric suction distribution due to grasses and propose a suction model. Besides, the significant matric suction could be related to shear strength enhancement and apply in slope stability analysis.

1.2 Problem Statement

The man-made and natural slopes are susceptible by weathering which lead to soil surface erosion, shallow failure and massive slope failure. Slope failure is a serious geology problem around the world especially in tropical rainforest region due to high rainfall intensity. The process of weathering had further weakening the subsoil profile in these regions. Malaysia Public Works Department (2008) reported that the factors which triggering landslide included rainfall (57.5%), water level change (35%), loading change (5%), slope geometry and vegetation change (2.5%). It had caused huge properties damage and lots of injuries as well as fatalities. The increasing of soil moisture and pore water pressure might be the main factor decreasing the soil strength thus leading to the slope stability problem. The most common slope failure happened in Malaysia is shallow landslide which is not more than 4 m in depth and happens during the rainfall season (Ali *et al.*, 2000). A shallow failure is not fatal but it could increases the rate of weathering and decreases the soil strength which will lead to a series of problem. Therefore, the surface protection and soil moisture variation in soil is very important in geotechnical engineering.

Bioengineering approach has become a popular method to improve slope stability since rising of the environmental issues. This approach utilizes plant or vegetation to reduce erosion and improve shear strength of soil. Such approach could beneficial in three aspects, environment, mechanical, and hydrological. Vegetation could counter the rising of carbon dioxide level, reinforce the soil and reduce surface erosion through rooting system. Besides, it could reduce runoff and lower pore water pressure through evapotranspiration process. The effect of vegetation can be classified into root reinforcement, soil moisture depletion, slope buttressing and arching (Fan and Su, 2009). Devkota *et al.* (2006) proved that bioengineering application is more cost-effective compared to conventional engineering method. However, combination of structural and vegetation solution is more cost-effective according to the field studies by Tuttle *et al.* (1992).

There are a lot of research had been done about the plant or tree root system (Brown and Sheu, 1975; Wu *et al*., 1979; Ziemer and Swanston, 1977; Indraratna *et al*., 2006; Nakamura *et al*., 2007; Ali and Rees, 2006). Some of them have investigated the moisture depletion and root water uptake (Prasad, 1988; Ojha and Rai, 1996; Mathur and Rao, 1999; Li *et al*., 2001; Vrugt *et al*., 2001a; Dardanelli *et al*., 2004; Raats, 2007; Shankar *et al*., 2013) but rare on the grass evapotranspiration (Woon *et al*., 2011; Ng *et al*., 2013; Ng *et al*., 2014; Rahardjo *et al*., 2014, Garg *et al*., 2015).

Woon (2013) studied the soil suction retention after rainfall due to Cynodon dactylon in laboratory modelling and field measurement. Ng *et al.* (2014) investigated the suction retention and influence zone of suction in vegetated soil with certain degree of relative compaction. Recently, Leung *et al.* (2015) compared the effects of tree root-induced change to soil water retention curve with suction responses due to root water uptake in vegetated soil. Besides, Leung *et al.* (2014) investigated the effects of grass to soil suction during evapotranspiration and ponding. The vegetated field was recognised potential in reduce infiltration and improve slope stability upon rainfall. Leung (2016) also compared 3 cases of study which showed the responses of suction in slopes due to grass. Suction induced in grassed slope could be lower than bare slope in certain condition and suction retention also depends on type of soil. There were so many studies had been done on bioengineering methods and contributions, the outcome of research seem not applied into slope design.

Although this application to the slope design was not popular, some common types of low cost grasses were practically acted as the finisher on the slope. The root system of grass may contributes to water uptake and evapotranspiration which produce matric suction and increase the soil strength in term of hydrological and mechanical enhancement. Therefore, the effect of common grass cover toward slope stability was the main focus in this study. The study focused on the common grass, Axonopus Compressus which covered almost whole campus of Universiti Teknologi Malaysia (UTM), Skudai Malaysia. The aim of this study is to understand the effect of grass to soil enhancement and shallow slope stability. The matric suction induced and changes of moisture content in soil due to grass are the major measurement in the study. The estimated moisture content, anticipated suction and result analysis can be obtained easily and faster with the help of computer program. In short, the development of the coding program on the water deficit curve and suction model is very useful to geo-environment development.

1.3 Objectives

The aim of this study is to explore the suction profile in soil due to the evapotranspiration of grass. The changes of soil water content or matric suction will be analysed and compared with the other models. To achieve this aim, several objectives of study are fixed as below:

I. To investigate the soil matric suction data at field and rate of evapotranspiration due to Axonopus Compressus.

II. To determine the soil drying pattern in field covered by Axonopus Compressus and develops a suction model formulation.

III. To develop a computer program that includes several popular water uptake models and suction model which could provide suction profile estimation.

IV. To compare the effect of grass induced suction to slope stability.

1.4 Scope of Study

This study will present the soil water changes or matric suction variation due to the water uptake process and evapotranspiration of grass in a field on unsaturated soil. It focuses on the hydrological-suction pattern within the influence zone of grass evapotranspiration. The parameters investigated are soil water deficit curve, total water extraction, matric suction, volumetric water content and grass evapotranspiration. The mechanical enhancement by roots tensile strength is lightly touched in this study to show the contribution of grass to the strength of soil.

The work consider the effect of existing common cow grass (Axonopus Compressus) field with the determination of root zone patterns limited to a depth within 0.5 m. This study focus on cow grass because it is common, relatively easy to maintain, good weather resistance and no problem with major diseases. The rooting depth is fixed as constant since the roots spread in random direction and concentrate on surface area. The rate of evapotranspiration of grass was investigated through concept of total weight loss in a day. The matric suction profiles were recorded by field instruments monitoring. However, the study only present the influence of suction induced to shear strength enhancement by Greenwood general equation (Greenwood *et al*., 2004) in program SLIP4EX (Greenwood, 2006). Other than that, a one-dimensional suction model is proposed and developed a computer programming to estimate the soil suction distribution.

A series of field monitoring program and laboratory experiments were analysed to determine the relationship of field evapotranspiration and grass rooting depth to matric suction distribution. In addition, the field monitoring result provided the reference for input parameters to apply in the numerical model and slope stability analysis. The site measurement data was verified with another study of grass in subtropical climate area. The proposed model was validated with the site measurement and the computer program was verified true by a complete set of test plan. The effect of grass induced suction and root tensile strength were compared to determine the contribution of grass toward unsaturated slope stability in term of hydrological and mechanical aspect.

1.5 Significance of the Study

The outcome of this study might be utilised as a reference input parameter of suction in the grass-covered which exist in soil within the unsaturated zone. It contributes to a set of history field suction data of Axonopus Compressus grass that is still rare in the research. The determination of the soil water characteristic curve and evapotranspiration of grass could be an alternative low cost measurement. The specific benefits that could be gained from this study including:

I. Providing essential quantification information on the behaviour of soil matric suction or negative pore water pressure variation in relation to grass evapotranspiration due to drying and precipitation.

II. Development of a grass suction induced model and coding program which could estimate the matric suction profile in the soil by water uptake models and relationship of soil water and suction.

III. Provide the shallow slope stability analysis with the existence of grass which includes suction induced and root tensile strength as well as the effect of suction to factor of safety when the soil parameters are varied.

IV. The computer program estimates the soil drying condition at grass-covered field effectively by grass rooting depth and evapotranspiration. The comparison between types of grass could be made and decide which grass to be used based on the requirement.

Grass is an important cover to soil because it reduces infiltration and increases surface runoff. The grass field evapotranspiration also strengthening the soil by extract and drain out the water in soil. The protection at top layer of slope is very important to avoid any further problem causes by shallow soil failure.

1.6 Thesis Structure and Organization

This thesis is structured into seven chapters: Chapter 1 *(Introduction),* Chapter 2 (*Literature Review),* Chapter 3 *(Research Methodology),* Chapter 4 *(Preliminary Data),* Chapter 5 *(Suction Model & Coding Program),* Chapter 6 (*Slope Stability Analysis Based on Grass Induces Suction*) *and* Chapter 7 *(Conclusions).* A brief introduction was often provided at the beginning of each chapter and concluding remarks at the end of the chapter to briefly summarize the content of the chapter.

As introduction to generally describe the background of problem related to geo-environmental problem associated with tree and water content changes have been discussed in Chapter 1. Apart from this problem statement, Chapter 1 also discusses the objectives, scopes and limitation as well as significance of the research. The brief description of bio-engineering methods in slope stability enhancement in term of mechanical and hydrological are presented.

Chapter 2 provides the previous research work and extensive review of literature that related the research topic. This chapter provides descriptions and concepts of theories published in literature pertaining on analysis of tree water uptake in unsaturated soil. Besides, this chapter also outlines methodologies of the laboratory work, field monitoring work, bio-engineering technique, and slope stability analysis that employed in the previous studies.

Chapter 3 describes the research methodology adopted in this study, particularly laboratory experiments and field monitoring program. Other than that, Chapter 3 also describes the detail of the equipment and procedures followed in order to achieve the objectives of the study. The method adopted in the laboratory experiments, field monitoring works, model formulation and limit equilibrium approach are well explained under this chapter.

The following chapters in this thesis are related to the discussions of data, results and analyses, i.e. Chapter 4, Chapter 5 and Chapter 6. Chapter 4 presents and discusses the preliminary data obtained from laboratory experiments and field monitoring as described in Chapter 3. These results include the soil characterization, basic properties, rate of evapotranspiration of grass, parameters of soil water characteristic curve and the response of matric suction distribution particularly influence by grass field.

Chapter 5 presents the formulation of suction model followed by the coding program. The field monitoring data were analysed to obtain the drying pattern of suction and the steps formulation of suction model were discussed. The coding program focused on some water uptake models and matric suction profile estimation. The chapter was concluded with verification of coding program with a series of complete test plan.

Chapter 6 considered on how much the influence of matric suction generated by grass field in the assessment of the stability on unsaturated soil slope. The typical of engineered slope geometry and shear strength of soil affected by matric suction were examined. The unsaturated slope stability analysis was presented with and without the effect of induced matric suction with simulation of slope geometry and soil properties. In addition, the influence of matric suction to factor of safety due to the variation of analysed parameters was discussed.

Lastly, the final chapter of the thesis (Chapter 7) covers the overall summary and conclusions of the thesis drawn from the present study as well as the recommendations for further researches on the subject.

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