SOIL SUCTION MODEL FOR GRASS EVAPOTRANSPIRATION

ONG CHOON KIAN

UNIVERSITI TEKNOLOGI MALAYSIA
SOIL SUCTION MODEL FOR GRASS EVAPOTRANSPIRATION

ONG CHOON KIAN

A thesis submitted in fulfilment of the requirements for the award of the degree of Doctor of Philosophy (Civil Engineering)

Faculty of Civil Engineering
Universiti Teknologi Malaysia

JULY 2017
I declare that entitled "Soil Suction Model For Grass Evapotranspiration" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature: 
Name: ONG CHOON KIAN
Date: 25 JULY 2017
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.
ACKNOWLEDGEMENT

My deepest gratitude goes to my most merciful God who has provided everything needed to complete this project for which it was undertaken for. Throughout this entire study, He took care of all that would stop me in my paths and strengthened me even through my most difficult periods.

At this juncture, I wish to express my gratitude and appreciation to all who contributed toward the success of this research. First and foremost, my sincere gratitude and appreciation goes to my thesis advisor, Assoc. Prof. Dr. Nazri Bin Ali for the critics, dedication, encouragement, ideas and passionate throughout this research. Without his proper guidance and assistance, this thesis would not possible to be accomplished on time. Besides, I am grateful to my external co-supervisor, Dr. Mohd Fakhirrazi Ishak from Infrastructure Management of University Malaysia Pahang for his assistance, contribution and advice during the course of the research.

I would like to extend my appreciation to all the Staff and Technicians of Department of Geotechnic & Transportation, FKA, UTM. I would like to express my appreciation for their help and assistance in the field and laboratory works. Sincere gratitude must be given to my fellow academicians, researchers, friends and colleagues for their involvements in any part of the research. Last but not least, I am deeply appreciated the continuous support, love and encouragement from my beloved family along my hard time to accomplish my thesis.
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 dilapisi 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 dilakukan daripada Ogos sehingga Disember 2015 untuk mengumpulkan data sedutan matrik degan menggunakan alat “jet-filled tensiometer”. Data yang dikumpul menunjukkan bahawa terdapat curah air kurang daripada 10 mm selama 5 hari sepanjang 5 bulan tersebut. Profil sedutan menunjukkan bahawa perubahan yang lebih besar di zona akar (< 30 cm) dan kesan sedutan berkurang di tahap yang lebih dalam. Kawasan kajian tersebut tidak berjaya mengekalkan sedutan tanah yang dijenama 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 hujan dengan penyejatan yang lebih rendah iaitu 0.4-0.9 mm sehari. Kadar evapotranspirasi boleh mencapai sehingga 3.0-6.0 mm sehari pada hari yang biasa. Satu persamaan matematik telah dicadangkan untuk mensimulasikan perubahan pengambilan air dalam tanah. Persamaan tersebut merangkumi kedalaman akar dan evapotranspirasi rumput. Ia berfungsi untuk menganggarkan profil sedutan tanah selesa selepas tempoh pengeringan tertentu. Model sedutan yang dicadangkan dan beberapa model pengambilan air telah dikodkan ke dalam program 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 lebih disahkan 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 keruntuan telah meningkat sebanyak 0.6-4.8% di beberapa 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 dari perubahan kekakalan 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

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DECLARATION</td>
<td>ii</td>
</tr>
<tr>
<td></td>
<td>DEDICATION</td>
<td>iii</td>
</tr>
<tr>
<td></td>
<td>ACKNOWLEDGEMENTS</td>
<td>iv</td>
</tr>
<tr>
<td></td>
<td>ABSTRACT</td>
<td>v</td>
</tr>
<tr>
<td></td>
<td>ABSTRAK</td>
<td>vi</td>
</tr>
<tr>
<td></td>
<td>TABLE OF CONTENTS</td>
<td>vii</td>
</tr>
<tr>
<td></td>
<td>LIST OF TABLES</td>
<td>xi</td>
</tr>
<tr>
<td></td>
<td>LIST OF FIGURES</td>
<td>xiii</td>
</tr>
<tr>
<td></td>
<td>LIST OF ABBREVIATIONS</td>
<td>xviii</td>
</tr>
<tr>
<td></td>
<td>LIST OF SYMBOLS</td>
<td>xx</td>
</tr>
<tr>
<td></td>
<td>LIST OF APPENDICES</td>
<td>xxii</td>
</tr>
</tbody>
</table>

1 INTRODUCTION 1
1.1 Background 1
1.2 Problem Statement 3
1.3 Objectives 5
1.4 Scope of Study 6
1.5 Significance of Study 7
1.6 Thesis Structure and Organization 8

2 LITERATURE REVIEW 10
2.1 Introduction 10
2.2 Root Water Uptake 11
   2.2.1 Context and significance 11
2.2.2 Root Water Uptake Process 13
2.2.3 Transpiration and Evapotranspiration 14

2.3 Water Uptake Model 16
  2.3.1 One-Dimensional Water Uptake 16
  2.3.2 Multi-Dimensional Water Uptake 21

2.4 Water Uptake Model Formulation 23
  2.4.1 Linear Model (Prasad) 23
  2.4.2 O-R Model (Ojha & Rai) 27
  2.4.3 Exponential Model (Li et al., 1999) 29
  2.4.4 Water Stress Compensation Exponential Model (Li et al., 2001) 33

2.5 Slope Stability 34
  2.5.1 Soil Bioengineering Technique 36
  2.5.2 Use of Vegetation 37

2.6 Grass In Malaysia 40
  2.6.1 Characteristic of Grass 41
  2.6.2 Application of Grass in Malaysia 42

2.7 Relationship of Soil Water and Suction 45
  2.7.1 Water Retention Curve (WRC) 46
  2.7.2 Soil Water Characteristic Curve (SWCC) 47

2.8 Induced suction by Grass Evapotranspiration 49
  2.8.1 Field & Laboratory Investigation of Bermuda Grass Induced Suction & Distribution (Woon, 2013) 50
  2.8.2 Experimental Investigation of Induced Suction Distribution in a Grass-covered Soil (Ng et al., 2013) 52
  2.8.3 Effects of soil Density on Grass-induced suction Distributions in Compacted Soil subjected to Rainfall (Ng et al., 2013) 55
  2.8.4 Comparisons of soil suction induced by evapotranspiration and transpiration of S. heptaphylla (Grag et al., 2015) 57
  2.8.5 Grass Evapotranspiration-induced suction in slope (Leung, 2016) 61

2.9 Assessment of Contribution of Vegetation 64

2.10 Program SLIP4EX 68
2.11 Concluding Remarks

3 RESEARCH METHODOLOGY

3.1 Introduction
3.2 Parameter Analysis
3.3 The Study Area
3.4 Soil Characteristic
3.5 Soil Water Characteristic Curve
3.6 Grass Evapotranspiration
3.7 Tensiometer Installation & Field Monitoring
3.8 Model Development
3.9 Slope Analysis
3.10 Concluding Remarks

4 PRELIMINARY DATA

4.1 Introduction
4.2 Index Properties & Soil Classification
4.3 Soil Water Characteristic Curve
4.4 Rate of Evapotranspiration
4.5 Field Monitoring Results
  4.5.1 Maximum & Minimum Drying Condition
  4.5.2 Verification of Site Measurement
4.6 Concluding Remarks

5 SUCTION MODEL & CODING PROGRAM

5.1 Model Development
5.2 Coding Program
  5.2.1 Program Verification
5.3 Suction Model VS Water Uptake Models
5.4 Concluding Remarks

6 SLOPE STABILITY ANALYSIS BASED ON GRASS-INDUCED SUCTION

6.1 Introduction
6.2 Site Location & Slope Geometry 145
6.3 Slope Stability Analysis 146
  6.3.1 Shallow Slope Stability 147
  6.3.2 Sensitivity Analysis 150
  6.3.3 Comparison between Effect of Grass 154
6.4 Concluding Remarks 155

7 CONCLUSIONS 158
7.1 Summary 158
7.2 Overall Conclusions 159
  7.2.1 Soil Properties & Classification 160
  7.2.2 Rate of Evapotranspiration of Grass 160
  7.2.3 Distribution of Matric Suction Profiles 161
  7.2.4 Model Development & Computer Program 162
  7.2.5 Slope Stability Analysis 162
7.6 Recommendations for Future Studies 164

REFERENCES 166

Appendices A - E 179-261
## LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE NO.</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 (a)</td>
<td>Transpiration rate for trees</td>
<td>15</td>
</tr>
<tr>
<td>2.1 (b)</td>
<td>Evapotranspiration rate of turf grass in North America (Kim and Beard, 1988)</td>
<td>15</td>
</tr>
<tr>
<td>2.2</td>
<td>Root diameter and tensile strength of grasses</td>
<td>44</td>
</tr>
<tr>
<td>2.3</td>
<td>Soil properties of five example of soils</td>
<td>47</td>
</tr>
<tr>
<td>2.4</td>
<td>Details comparison between the field monitoring of three history cases</td>
<td>62</td>
</tr>
<tr>
<td>2.5</td>
<td>Example of slices data for SLIP4EX analysis</td>
<td>70</td>
</tr>
<tr>
<td>2.6</td>
<td>Example of parameters which reflect the contribution of vegetation</td>
<td>70</td>
</tr>
<tr>
<td>4.1</td>
<td>Summary of soil properties in the study area</td>
<td>91</td>
</tr>
<tr>
<td>4.2</td>
<td>Fitting parameters of the soil for Van Genuchten model</td>
<td>92</td>
</tr>
<tr>
<td>4.3</td>
<td>Data weight of sample in grams to determine evapotranspiration</td>
<td>93</td>
</tr>
<tr>
<td>4.4</td>
<td>Rate of soil evaporation and evapotranspiration of Axonopus Compressus</td>
<td>94</td>
</tr>
<tr>
<td>4.5</td>
<td>The rate of daily evapotranspiration of Axonopus Compressus in unit mm/day from August to December 2015</td>
<td>105</td>
</tr>
<tr>
<td>4.6</td>
<td>The highest suction (kPa) induced by evapotranspiration of Axonopus Compressus</td>
<td>112</td>
</tr>
<tr>
<td>4.7</td>
<td>The lowest suction (kPa) retained by grass Axonopus Compressus</td>
<td>113</td>
</tr>
<tr>
<td>4.8</td>
<td>Details comparison between both studies</td>
<td>114</td>
</tr>
</tbody>
</table>
5.1 Summary of the suction models for field Axonopus compressus  120
5.2 Comparison of matric suction profiles between model and measured data  122
5.3 The summary of test plan for the suction water uptake models in the coding program  133
5.4 The summary of test plan for the SWCC and matric suction estimation in the coded program  135
5.5 The summary of modelled grass field suction distributions at day-10  141
6.1 The summary of parameters simulation in sensitivity analysis  146
6.2 (a) The contribution of suction to factor of safety in unsaturated slope with varied slope angle  152
6.2 (b) The contribution of suction to factor of safety in unsaturated slope with varied cohesion of soil  153
6.2 (c) The contribution of suction to factor of safety in unsaturated slope with varied soil friction angle  153
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE NO.</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Water use by trees modified after Nisbet (2005)</td>
<td>14</td>
</tr>
<tr>
<td>2.2</td>
<td>Several water uptake distributions with depth (Vrugt et al., 2001a)</td>
<td>20</td>
</tr>
<tr>
<td>2.3</td>
<td>Measurement of soil water content profiles and simulation results from different root water uptake models (Li et al., 1999)</td>
<td>31</td>
</tr>
<tr>
<td>2.4</td>
<td>Estimated maximum soil water uptake by different b values, the linear model and constant-extraction-rate model with PT set at 0.4 cm(^d) (Li et al., 1999)</td>
<td>31</td>
</tr>
<tr>
<td>2.5</td>
<td>Soil water content profiles simulated by exponential model with different b values (Li et al., 1999)</td>
<td>32</td>
</tr>
<tr>
<td>2.6</td>
<td>Maximum soil water uptake ((S_{\text{max}})). Curves A and E, (b = 0.025); curves B and F, (b = 0.05); curve C, (b = 0.1) and curve D, (b = 0.15), PT at 0.4 cm(^d) (Li et al., 1999)</td>
<td>32</td>
</tr>
<tr>
<td>2.7</td>
<td>Estimated maximum water uptake under non-water stress conditions</td>
<td>34</td>
</tr>
<tr>
<td>2.8</td>
<td>Several types of root system of plants (after Yen, 1987)</td>
<td>39</td>
</tr>
<tr>
<td>2.9</td>
<td>Use of Vetiver grass for erosion control and slope stabilization</td>
<td>42</td>
</tr>
<tr>
<td>2.10</td>
<td>Deep roots of vetiver grass as contour hedges for water control (Adapted from Vetiver, 1990)</td>
<td>43</td>
</tr>
<tr>
<td>2.11</td>
<td>Detailed typical SWCC for silty soil</td>
<td>47</td>
</tr>
<tr>
<td>2.12</td>
<td>Example of SWCC for various range of soil</td>
<td>48</td>
</tr>
<tr>
<td>2.13</td>
<td>Matric suction measurement for grassed and bare soil at 10 cm depth and the corresponding rainfall intensity from 28-May until 30-June 2012</td>
<td>50</td>
</tr>
<tr>
<td>2.14</td>
<td>Matric suction measurement for grassed and bare soil at 30 cm depth and the corresponding rainfall intensity from 28-May until 30-June 2012</td>
<td>51</td>
</tr>
</tbody>
</table>
2.15 Matric suction comparison between grassed and bare soil plots after 3 and 6 days of drying period (3 to 9-June 2012) 51
2.16 Matric suction retained in grassed and bare soil plots after rainfall on 10-June 2012 52
2.17 (a) Suction profiles in grassed and bare soil for specific drying periods 53
2.17 (b) Suction profiles variation in grassed and bare soil with lateral distance 53
2.18 Suction retained after ponding for three replicates sample 54
2.19 Rate of infiltration with time for bare and vegetated soil 56
2.20 Induced suction profiles of bare and vegetated silty sand at 30 cm depth 57
2.21 (a) Measured RAI profiles for five samples tested in first test 58
2.21 (b) Measured RAI profiles for five samples tested in second test 58
2.22 (a) Comparisons of suction profiles between samples at 80 mm depth 59
2.22 (b) Comparisons of rates of T and ET between test samples T1 & T5 59
2.23 Comparison of suction distributions between bare and vegetated samples after 7 days of drying 60
2.24 (a) & (b) Measured suction profiles for bare soil and pasture upon drying for (a) 3 days (b) 7 days in Singapore 61
2.24 (c to f) Measured suction profiles upon drying for cases South Korea (c & d) and USA (e & f) 63
2.25 Interaction between roots system and soil with (a) single root; (b) multiple branches; (c) multiple branches with full interaction 66
2.26 Parameter enhanced zones due to consistent vegetation 66
2.27 The parameters and dimensions required in slope stability analysis 69
2.28 The results obtained after consider vegetation effect in different methods by SLIP4EX 71
3.1 Flow chart of research 77
3.2 (a) Location of field monitoring in front of block P18 78
3.2 (b) Location of field monitoring free from effect of tree 79
3.3 Calibration of relationship between matric suction and water content of soil sample

3.4 The grasses from field monitoring were transferred and planted in the flowerpot

3.5 The bare soil and grassed samples were exposed to environment for drying

3.6 The labelled jet-filled tensiometer installed at the study field

3.7 Field monitoring by jet-filled tensiometers in 5 different depths at the study area

3.8 The jet-filled tensiometers in study area were fenced with geotextile

3.9 Details of grassed slope

3.10 Output of several limit equilibrium approaches

4.1 Particle size distribution of soil sample

4.2 The SWCC (desorption) of the soil at study area

4.3 Daily evapotranspiration of Axonopus compressus in August 2015

4.4 Daily evapotranspiration of Axonopus compressus in September 2015

4.5 Daily evapotranspiration of Axonopus compressus in October 2015

4.6 Daily evapotranspiration of Axonopus compressus in November 2015

4.7 Daily evapotranspiration of Axonopus compressus in December 2015

4.8 (a) Day evapotranspiration of Axonopus compressus in August 2015

4.8 (b) Night evapotranspiration of Axonopus compressus in August 2015

4.9 (a) Day evapotranspiration of Axonopus compressus in September 2015

4.9 (b) Night evapotranspiration of Axonopus compressus in September 2015

4.10 (a) Day evapotranspiration of Axonopus compressus in October 2015

4.10 (b) Night evapotranspiration of Axonopus compressus in October 2015

4.11 (a) Day evapotranspiration of Axonopus compressus in November 2015
4.11 (b) Night evapotranspiration of Axonopus compressus in November 2015 103
4.12 (a) Day evapotranspiration of Axonopus compressus in December 2015 104
4.12 (b) Night evapotranspiration of Axonopus compressus in December 2015 104
4.13 Comparison between surface of bare soil sample and grassed sample 106
4.14 Measured matric suction profile of soil covered by Axonopus compressus in August 2015 108
4.15 Measured matric suction profile of soil covered by Axonopus compressus in September 2015 109
4.16 Measured matric suction profile of soil covered by Axonopus compressus in October 2015 110
4.17 Measured matric suction profile of soil covered by Axonopus compressus in November 2015 110
4.18 Measured matric suction profile of soil covered by Axonopus compressus in December 2015 111
4.19 Comparison of matric suction profiles between Cynodon dactylon in Hong Kong and Axonopus compressus in Johor, Malaysia for 6 days drying period 115
5.1 Field suction distributions from 21-Aug to 30-Aug 2015 118
5.2 Field suction distributions from 14-Oct to 23-Oct 2015 119
5.3 Field suction distributions from 18-Dec to 27-Dec 2015 120
5.4 Measured suction profiles and simulation outputs in grassed sandy silt soil 122
5.5 Example flowchart of model of Li et al. 2001 (F) 124
5.6 The page for water uptake model selection and its equation 125
5.7 (a) Data input for model from Ojha and Rai 126
5.7 (b) Data input for model from Wu et al. 126
5.7 (c) Data input for model from Li et al. 127
5.8 (a) The example of calculated result for Ojha and Rai model 127
5.8 (b) The example of calculated result for Wu et al. model 127
5.8 (c) The example of calculated result for Li et al. model 128
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.9</td>
<td>Matric suction estimation for continuous drying period by water uptake model</td>
<td>128</td>
</tr>
<tr>
<td>5.10</td>
<td>Soil suction profiles for maximum 10 days of drying period</td>
<td>130</td>
</tr>
<tr>
<td>5.11</td>
<td>The output of Ong et al. model</td>
<td>131</td>
</tr>
<tr>
<td>5.12</td>
<td>Volumetric water content of soil which converted from suction profile</td>
<td>131</td>
</tr>
<tr>
<td>5.13</td>
<td>Combination of outputs for six water uptake models</td>
<td>132</td>
</tr>
<tr>
<td>5.14</td>
<td>The outputs of water uptake models with input parameters of study grass field</td>
<td>140</td>
</tr>
<tr>
<td>5.15</td>
<td>The comparison of grass field suction profiles between suction and water uptake models</td>
<td>142</td>
</tr>
<tr>
<td>6.1</td>
<td>Location of study slope that covered by grass Axonopus Compressus</td>
<td>145</td>
</tr>
<tr>
<td>6.2</td>
<td>Details of grass covered slope being analysed</td>
<td>145</td>
</tr>
<tr>
<td>6.3</td>
<td>Saturated and unsaturated analysis of slope with slip plane up to 0.5 m</td>
<td>148</td>
</tr>
<tr>
<td>6.4</td>
<td>Effect of grass in term of suction and tensile strength to slope stability</td>
<td>149</td>
</tr>
<tr>
<td>6.5</td>
<td>Safety factor of slope with suction effect for various slope angles</td>
<td>150</td>
</tr>
<tr>
<td>6.6</td>
<td>Safety factor of slope with suction effect when cohesion is varied</td>
<td>151</td>
</tr>
<tr>
<td>6.7</td>
<td>Safety factor of slope with suction effect when friction angle is varied</td>
<td>152</td>
</tr>
<tr>
<td>6.8</td>
<td>Safety factor of slope in saturated and drying condition due to Axonopus Compressus and Cynodon Dactylon.</td>
<td>154</td>
</tr>
</tbody>
</table>
LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1D</td>
<td>1-dimensional</td>
</tr>
<tr>
<td>2D</td>
<td>2-dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>3-dimensional</td>
</tr>
<tr>
<td>SLIP4EX</td>
<td>A program for routine slope stability analysis</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>A</td>
<td>Area</td>
</tr>
<tr>
<td>AC</td>
<td>Axonopus Compressus</td>
</tr>
<tr>
<td>B</td>
<td>Bare</td>
</tr>
<tr>
<td>BS</td>
<td>British Standard</td>
</tr>
<tr>
<td>CD</td>
<td>Cynodon Dactylon</td>
</tr>
<tr>
<td>D</td>
<td>Depletion</td>
</tr>
<tr>
<td>ET</td>
<td>Evapotranspiration</td>
</tr>
<tr>
<td>FX</td>
<td>Fredlund &amp; Xing</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>G</td>
<td>Grass</td>
</tr>
<tr>
<td>HA</td>
<td>Highway Agency</td>
</tr>
<tr>
<td>LAI</td>
<td>Leaf area index</td>
</tr>
<tr>
<td>LL</td>
<td>Liquid limit</td>
</tr>
<tr>
<td>O-R</td>
<td>Ojha &amp; Rai</td>
</tr>
<tr>
<td>PL</td>
<td>Plastic limit</td>
</tr>
<tr>
<td>PI</td>
<td>Plasticity index</td>
</tr>
<tr>
<td>PT</td>
<td>Potential transpiration</td>
</tr>
<tr>
<td>RC</td>
<td>Relative compaction</td>
</tr>
<tr>
<td>RAI</td>
<td>Root area index</td>
</tr>
<tr>
<td>RLD</td>
<td>Root length density</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------------------------</td>
</tr>
<tr>
<td>SWCC</td>
<td>Soil water characteristic curve</td>
</tr>
<tr>
<td>dbh</td>
<td>Trunk diameter</td>
</tr>
<tr>
<td>UD</td>
<td>Undisturbed</td>
</tr>
<tr>
<td>USCS</td>
<td>Unified soil classification system</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>USA</td>
<td>United State of America</td>
</tr>
<tr>
<td>UTM</td>
<td>Universiti Teknologi Malaysia</td>
</tr>
<tr>
<td>VG</td>
<td>Van Genuchten</td>
</tr>
<tr>
<td>w.c.</td>
<td>Water content</td>
</tr>
<tr>
<td>WRC</td>
<td>Water retention curve</td>
</tr>
</tbody>
</table>
**LIST OF SYMBOLS**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>Actual water uptake</td>
</tr>
<tr>
<td>$c_v'$</td>
<td>Additional cohesion</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Angle between direction of $T$ and slip surface</td>
</tr>
<tr>
<td>$u$</td>
<td>Average water pressure</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Base angle</td>
</tr>
<tr>
<td>$c'$</td>
<td>Cohesion</td>
</tr>
<tr>
<td>$D$</td>
<td>Depletion</td>
</tr>
<tr>
<td>$z$</td>
<td>Depth</td>
</tr>
<tr>
<td>$T_{rd}$</td>
<td>Design root force</td>
</tr>
<tr>
<td>$K$</td>
<td>Earth pressure coefficient</td>
</tr>
<tr>
<td>$b$</td>
<td>Empirical coefficient</td>
</tr>
<tr>
<td>$F$</td>
<td>Fraction of root length density</td>
</tr>
<tr>
<td>$\phi'$</td>
<td>Friction angle</td>
</tr>
<tr>
<td>$\Delta u_v$</td>
<td>Increase in average pore water pressure</td>
</tr>
<tr>
<td>$\Delta U_{1v}$</td>
<td>Increase in water force on left side of slice</td>
</tr>
<tr>
<td>$\Delta U_{2v}$</td>
<td>Increase in water force on right side of slice</td>
</tr>
<tr>
<td>$l$</td>
<td>Length</td>
</tr>
<tr>
<td>$W_v$</td>
<td>Mass of vegetation</td>
</tr>
<tr>
<td>$S_{max}$</td>
<td>Maximum water extraction</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of layer</td>
</tr>
<tr>
<td>$F_r$</td>
<td>Partial safety factor</td>
</tr>
<tr>
<td>$n$</td>
<td>Porosity</td>
</tr>
<tr>
<td>$T_p$</td>
<td>Potential transpiration</td>
</tr>
<tr>
<td>$h$</td>
<td>Pressure head</td>
</tr>
<tr>
<td>$\theta_r$</td>
<td>Residual water content</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td>$L_r$</td>
<td>Root length</td>
</tr>
<tr>
<td>$z_r$</td>
<td>Rooting depth</td>
</tr>
<tr>
<td>$K_s$</td>
<td>Saturated permeability</td>
</tr>
<tr>
<td>$\theta_s$</td>
<td>Saturated water content</td>
</tr>
<tr>
<td>$b$</td>
<td>Slice width</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Slope angle</td>
</tr>
<tr>
<td>$\alpha_a$</td>
<td>Soil water availability</td>
</tr>
<tr>
<td>$a_w$</td>
<td>Soil water available factor</td>
</tr>
<tr>
<td>$G_s$</td>
<td>Specific gravity</td>
</tr>
<tr>
<td>$\psi$</td>
<td>Suction</td>
</tr>
<tr>
<td>$T$</td>
<td>Tensile root / reinforcement force</td>
</tr>
<tr>
<td>$\Delta z$</td>
<td>Thickness of layer</td>
</tr>
<tr>
<td>$W$</td>
<td>Total water extracted</td>
</tr>
<tr>
<td>$T_{ru}$</td>
<td>Ultimate root force</td>
</tr>
<tr>
<td>$e$</td>
<td>Void ratio</td>
</tr>
<tr>
<td>$\theta_w$</td>
<td>Water content</td>
</tr>
<tr>
<td>$U_1$</td>
<td>Water force on left side of slice</td>
</tr>
<tr>
<td>$U_2$</td>
<td>Water force on right side of slice</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Weighted stress index</td>
</tr>
<tr>
<td>$\beta_w$</td>
<td>Wind direction in angle</td>
</tr>
<tr>
<td>$D_w$</td>
<td>Wind force</td>
</tr>
</tbody>
</table>
## LIST OF APPENDICES

<table>
<thead>
<tr>
<th>APPENDIX</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Flowchart of Computer Program</td>
<td>184</td>
</tr>
<tr>
<td>B</td>
<td>Laboratory Data to Measure Grass</td>
<td>196</td>
</tr>
<tr>
<td></td>
<td>Evapotranspiration</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Weather Report &amp; Field Monitoring Data 2015</td>
<td>208</td>
</tr>
<tr>
<td>D</td>
<td>Code of the Computer Program</td>
<td>214</td>
</tr>
<tr>
<td>E</td>
<td>Test Plan of Coding Program</td>
<td>261</td>
</tr>
</tbody>
</table>
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 so tir, 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.
REFERENCES


Woon, K. X. (2013). *Field and laboratory investigations of Bermuda grass induced suction and distribution*. Degree of Master of Philosophy. The Hong Kong University of Science and Technology.


