

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

MOHD FAKHRURRAZI BIN ISHAK

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

Faculty of Civil Engineering  
Universiti Teknologi Malaysia

OCTOBER 2014

## 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..

## TABLE OF CONTENTS

| CHAPTER | TITLE                     | PAGE  |
|---------|---------------------------|-------|
|         | <b>TITLE OF PROJECT</b>   | i     |
|         | <b>DECLARATION</b>        | ii    |
|         | <b>DEDICATION</b>         | iii   |
|         | <b>ACKNOWLEDGEMENT</b>    | iv    |
|         | <b>ABSTRACT</b>           | v     |
|         | <b>ABSTRAK</b>            | vi    |
|         | <b>TABLE OF CONTENTS</b>  | vii   |
|         | <b>LIST OF TABLES</b>     | xiv   |
|         | <b>LIST OF FIGURES</b>    | xvi   |
|         | <b>LIST OF SYMBOLS</b>    | xxiv  |
|         | <b>LIST OF APPENDICES</b> | xxvii |
|         | <br><b>INTRODUCTION</b>   | <br>1 |
| 1.1     | Background of the Study   | 1     |
| 1.2     | Problem Statement         | 4     |
| 1.3     | Objectives                | 5     |
| 1.4     | Scope of Study            | 6     |
| 1.5     | Significance of Study     | 7     |
| 1.6     | Thesis Organization       | 8     |

|          |  |    |
|----------|--|----|
| <b>2</b> | <b>LITERATURE REVIEW</b>   | 11 |
| 2.1      | Introduction   | 11 |
| 2.2      | Tropical Residual Soil   | 12 |
|          | 2.2.1 Formation and Degree of Weathering                                 | 13 |
| 2.3      | Unsaturated Soil Behavior  | 16 |
|          | 2.3.1 Soil Matric Suction  | 17 |
|          | 2.3.2 Soil Water Characteristic Curve<br>(SWCC)                          | 18 |
|          | 2.3.3 Hydraulic Conductivity Function                                    | 22 |
| 2.4      | Shear Strength of Unsaturated Soil                                       | 24 |
|          | 2.4.1 Axis Translation Technique   | 28 |
| 2.5      | Rainfall Infiltration  | 29 |
|          | 2.5.1 Infiltration On Slope Depth Of Wetting<br>Front And Redistribution | 29 |
| 2.6      | Richard's Equation   | 31 |
| 2.7      | Tree Water Uptake  | 33 |
|          | 2.7.1 Root Water Uptake Process  | 35 |
|          | 2.7.2 Transpiration  | 39 |
| 2.8      | Field Monitoring   | 41 |
| 2.9      | Numerical Simulation Of Tree Water Uptake<br>Model                       | 44 |
| 2.10     | Concluding Remarks   | 46 |

|          |  |           |
|----------|--|-----------|
| <b>3</b> | <b>RESEARCH METHODOLOGY</b>                                      | <b>48</b> |
| 3.1      | Introduction   | 48        |
| 3.2      | Parameters Analysis  | 51        |
| 3.3      | The Study Area   | 52        |
|          | 3.3.1 Topography   | 52        |
|          | 3.3.2 Regional Geology   | 53        |
|          | 3.3.3 Subsurface Investigation                                   | 56        |
| 3.4      | Soil Characterization  | 58        |
|          | 3.4.1 Soil Properties  | 58        |
| 3.5      | Index Properties Test  | 60        |
|          | 3.5.1 Laboratory Permeability Tests                              | 62        |
|          | 3.5.2 Determination of Soil Water<br>Characteristic Curve (SWCC) | 63        |
|          | 3.5.3 Mineralogy and Fabric Tests                                | 64        |
| 3.6      | Engineering Property Tests                                       | 65        |
|          | 3.6.1 Determination Unsaturated Shear Strength                   | 67        |
|          | 3.6.1.1 Determination Of Variation<br>Matric Suction             | 68        |
|          | 3.6.2 Unconsolidated Undrained Tests                             | 72        |
| 3.7      | Field Monitoring   | 72        |
|          | 3.7.1 Field Monitoring Work                                      | 73        |
|          | 3.7.2 Field Instrumentations                                     | 77        |
|          | 3.7.2.1 Installation Of Gypsum Block                             | 79        |
|          | 3.7.2.2 Installation Of Tensiometers                             | 81        |
|          | 3.7.2.3 Installation And Calibration Of<br>Rain Gauge            | 83        |

|          |         |   |     |
|----------|---------|---|-----|
|          | 3.8     | <i>Acacia Mangium</i> Tree                    | 85  |
|          | 3.9     | Gid Software Program                          | 86  |
|          | 3.10    | Numerical Modelling                           | 87  |
|          | 3.11    | Concluding Remarks                            | 88  |
| <b>4</b> |         | <b>PRELIMINARY DATA</b>                       | 90  |
|          | 4.1     | Introduction                                  | 90  |
|          | 4.2     | Residual Soil Profile                         | 91  |
|          | 4.3     | Soil Properties                               | 95  |
|          | 4.3.1   | Index Properties and Soil<br>Classifications  | 96  |
|          | 4.3.2   | Mineralogy and Microfabric<br>Characteristics | 101 |
|          | 4.3.3   | Engineering Properties                        | 123 |
|          | 4.3.3.1 | Shear Strength                                | 105 |
|          | 4.3.3.2 | Saturated Hydraulic<br>Conductivity           | 106 |
|          | 4.3.4   | Hydraulic Properties                          | 108 |
|          | 4.3.4.1 | Soil Water Characteristic<br>Curve (SWCC)     | 109 |
|          | 4.3.4.2 | Hydraulic Conductivity<br>Function            | 112 |
|          | 4.4     | Field Monitoring Result                       | 113 |
|          | 4.5     | Consolidated Isotropic Undrained Tests        | 138 |

|          |  |     |
|----------|--|-----|
| 4.6      | Suction Requirement In Unconsolidation<br>Undrained (UU)   | 139 |
| 4.6.1    | Unconsolidated Undrained Tests   | 140 |
| 4.6.2    | Unsaturated Shear Strength<br>Parameters   | 142 |
| 4.6.2.1  | Unsaturated Shear<br>Strength  | 142 |
| 4.7      | Unsaturated Shear Strength Behaviour<br>And Suction Variation  | 138 |
| 4.8      | Pattern Suction Distribution At Slope<br>Without Tree And 1m From Tree<br>Respond To Single Rainfall Event | 148 |
| 4.9      | Concluding Remarks   | 156 |
| <b>5</b> | <b>EFFECT OF TREE WATER UPTAKE ON<br/>SUCTION DISTRIBUTION</b>   | 158 |
| 5.1      | Introduction   | 158 |
| 5.2      | Rainfall Intensities Patterns  | 159 |
| 5.3      | Tropical Residual Soil Layer   | 161 |
| 5.3.1    | Infiltration To Wetting Front  | 163 |
| 5.4      | Analysed of <i>In-Situ</i> Matric Suction  | 166 |
| 5.4.1    | Pattern of Matric Suction Due To<br>Tree Water Uptake  | 166 |
| 5.4.2    | Matric Suction Profiles Due To<br>Tree Water Uptake  | 173 |
| 5.5      | Field Monitoring Representation  | 179 |



|          |       |   |     |
|----------|-------|---|-----|
|          | 5.5.1 | Matric Suction Contour Due To Tree<br>Water Uptake  | 180 |
|          | 5.6   | Concluding Remarks  | 182 |
| <b>6</b> |       | <b>ANALYSIS OF TREE INDUCE SUCTION ON<br/>SLOPE STABILITY</b>                               | 184 |
|          | 6.1   | Introduction  | 184 |
|          | 6.2   | Unsaturated Soil Slope  | 188 |
|          | 6.2.1 | Unsaturated Soil Shear Strength<br>Model  | 190 |
|          | 6.2.2 | Procedure to determine the non-<br>linear failure envelope                                  | 193 |
|          | 6.3   | Stability of Unsaturated Slopes   | 196 |
|          | 6.3.1 | Assessing Slope Stability   | 199 |
|          | 6.4   | Matric Suction Related To Factor Of<br>Safety (FOS)   | 203 |
|          | 6.4.1 | Tree Induce Suction Influence<br>Stability Of Slope   | 204 |
|          | 6.4.2 | Slope Stability Analyses  | 209 |
|          | 6.5   | Concluding Remarks  | 211 |
| <b>7</b> |       | <b>TREE INDUCE SUCTION AND<br/>NUMERICAL MODELLING</b>                                      | 213 |
|          | 7.1   | Introduction  | 213 |
|          | 7.2   | Comparison With Nonlinear Failure<br>Envelope   | 214 |
|          | 7.2.1 | Fitting of experimental results with<br>failure envelope (Fredlund <i>et al.</i> ,<br>1996) | 215 |

|          |  |           |
|----------|--|-----------|
| 7.3      | Development Of Soil Matric Suction<br>During Drying Season                 | 217       |
| 7.4      | The Water-Uptake Model   | 220       |
| 7.4.1    | Development of Two-Dimensional Axi-<br>Symmetric Water Uptake Equation     | 221       |
| 7.5      | Input Data From Laboratory Results   | 218       |
| 7.6      | Comparisons between Field and Simulated<br>modelling Suction Distributions | 227       |
| 7.6.1    | Numerical Simulation And Field Matric<br>Suction Measurements              | 227       |
| 7.7      | Concluding Remarks   | 231       |
| <b>8</b> | <b>CONCLUSIONS AND RECOMMENDATIONS</b>                                     | 233       |
| 8.1      | Summary  | 233       |
| 8.2      | Engineering Properties And Shear Strength<br>Envelop Of Residual Soils     | 235       |
| 8.3      | Distribution Of Matric Suction Profiles                                    | 223       |
| 8.4      | Non-linear shear strength envelop and FOS                                  | 237       |
| 8.5      | Numerical Simulation And Field<br>Measurements                             | 238       |
|          | <b>REFERENCES</b>  | 241       |
|          | Appendices A – G   | 262 – 320 |

**LIST OF TABLES**

| <b>TABLE NO.</b> | <b>TITLE</b>  | <b>PAGE</b> |
|------------------|---|-------------|
| 2.1              | Rooting information and relative water demands for some common tree species, modified after Crow (2004) | 38          |
| 2.2              | Transpiration rate for trees  | 40          |
| 3.1              | The regional geological succession stratigraphy and formation in the study area                         | 54          |
| 3.2              | Sources of the field identification system (Singh, 1992)  | 57          |
| 3.3              | Target moisture content values and target suctions  | 70          |
| 3.4              | Target weights for target suctions for unsaturated soil specimens                                       | 71          |
| 3.5              | Technical detail of instrument at study area  | 75          |
| 4.1              | The properties of the soil material in this study area  | 95          |
| 4.2              | Physical indices of residual soil from within Singapore - Johor Bahru - Kulai area                      | 99          |

|      |   |     |
|------|---|-----|
| 4.3  | Percentages of residual soil components based on grain size from within Singapore - Johor Bahru - Kulai area  | 100 |
| 4.4  | Mineral constituents obtained from XRD test   | 101 |
| 4.5  | Mineral compositions obtained from the mineralogy tests   | 102 |
| 4.6  | Shear strength properties of study area   | 105 |
| 4.7  | Engineering properties of residual soil from within Singapore-Johor Bahru – Kulai area  | 107 |
| 4.8  | SWCC parameters of the residual soils   | 110 |
| 4.9  | SWCC parameter of the residual soil (sandy SILT) from within Singapore-Johor Bahru-Kulai  | 111 |
| 4.10 | Undrained compressive strengths for UU tests for several ranges of suctions and cell pressures  | 141 |
| 4.11 | Unsaturated shear strength parameters ( $\phi^b$ , $C_{app}$ ) : (a) Specimens under cell pressure 20 kPa; (b) Specimens under cell pressure 50 kPa; (c) Specimens under cell pressure 100 kPa; (d) Specimens under cell pressure 200 kPa | 143 |
| 4.12 | Values of angle of frictional resistance to the contribution of matric suction ( $\phi^b$ ) in $A_{ev}$   | 147 |
| 4.13 | Reduction ratio of $\phi'$ for the highest suction pressure tested (300 kPa)  | 148 |
| 5.1  | Rainfall patterns used in infiltration analysis from 18th December to 23rd December 2011  | 160 |
| 5.2  | Rainfall patterns used in infiltration analysis from 31st February to 4th February 2012   | 160 |

|     |  |     |
|-----|--|-----|
| 5.3 | Depth of infiltration in soil layer on 18th December 2011, 19th December 2011 and 23rd December 2011 | 164 |
| 5.4 | Depth of infiltration in soil layer on 31st February 2012, 2nd February 2012 and 4th February 2012   | 165 |
| 6.1 | Experimental values of shear strength with value of $\phi^b$ angle of tropical residual soil         | 191 |
| 6.2 | Non-linear value of $\phi^b$ angle at several suction ranges   | 196 |
| 6.3 | Comparison of FOS by various methods of analysis   | 202 |

## LIST OF FIGURES

| FIGURE NO. | TITLE   | PAGE |
|------------|---|------|
| 2.1        | Classification of the weathering profile (McLean and Gribble, 1979)   | 15   |
| 2.2        | Typical vertical matric suction profile (Lee, 2008)   | 18   |
| 2.3        | Typical soil water characteristic curves (Fredlund and Xing, 1994)  | 20   |
| 2.4        | Soil water characteristic curves for sandy soil, a silty soil, and a clayey soil. (Fredlund and Xing, 1994) | 21   |
| 2.5        | Typical suction-dependent hydraulic conductivity function (Soilvision, 2007)                                | 23   |
| 2.6        | Extended Mohr-Coulomb failure envelopes for unsaturated soil (Fredlund and Rahardjo, 1993)                  | 26   |
| 2.7        | Volumetric water content and suction in the development of wetting front (Wang <i>et al.</i> , 2003)        | 31   |
| 2.8        | Water use by trees, modified after Nisbet (2005)  | 36   |
| 2.9        | Typical nature of root architecture at top of the river banks   | 39   |
| 3.1        | Flow chart of research methodology  | 50   |
| 3.2        | Location of <i>Acacia manggium</i> tree   | 52   |
| 3.3        | Regional geology of Johor Bahru-Skudai-Kulai (Burton, 1973)   | 55   |
| 3.4        | Field investigations (trial pit) at the study area  | 58   |

|      |   |    |
|------|---|----|
| 3.5  | Undisturbed samples was collected during field investigation (trial pit) at depth 1.5 m                                     | 59 |
| 3.6  | Constant head permeameter under testing   | 62 |
| 3.7  | Pressure plate extractor test setup in Universiti Putra Malaysia  | 64 |
| 3.8  | Consolidation Isotropic Undrained (CIU) Triaxial compression test   | 67 |
| 3.9  | Two unsaturated soil specimen inside the oven to decrease moisture content and weights to reach target weights              | 70 |
| 3.10 | Cross-sectional view of the research plot design at Faculty of Electrical Engineering, UTM                                  | 74 |
| 3.11 | Jet-fill Tensiometers and Gypsum Moisture Blocks are installed at Station Slope area according to depth                     | 75 |
| 3.12 | Jet-fill Tensiometers and Gypsum Moisture Blocks are installed at Station Flat according to depth                           | 76 |
| 3.13 | <i>Acacia mangium</i> tree located at the toe of slope with position of instrument (tensiometer, gypsum block & rain gauge) | 77 |
| 3.14 | Calibration and capability of Tensiometer and Gypsum blocks   | 79 |
| 3.15 | a) Gypsum block installed at the study area b) The gypsum block is connected to lead wires meter reader                     | 80 |
| 3.16 | Meter reading on the suction Soil Moisture Observation Chart  | 81 |
| 3.17 | Tensiometer installed at field study  | 82 |
| 3.18 | Rain gauge at study area  | 84 |
| 3.19 | <i>Acacia mangium</i> tree at toe of slope  | 85 |
| 3.20 | <i>Acacia mangium</i> leaves  | 86 |

|      |  |             |
|------|--|-------------|
| 4.1  | Field scale of trial pit toward Face A, B and C  | 92          |
| 4.2  | Interpretation of profile residual soil from Faculty of Electrical Engineering   | 93          |
| 4.3  | General subsurface profile of Faculty of Electrical Engineering  | 94          |
| 4.4  | Particle size distribution of tropical residual soil (sandy SILT)  | 97          |
| 4.5  | Grade VI residual soil of sandy SILT, magnified 200 times using a scanning electron microscope (SEM)   | 103         |
| 4.6  | Sandy SILT using magnified 500 scanning electron microscope (SEM), shows typical subangular blocky of mineral  | 104         |
| 4.7  | The soil-water characteristic curves (SWCC) of the residual soils  | 109         |
| 4.8  | Hydraulic conductivity function with responds to matric suction of the residual soils predicted by using Van Genutchten's method (1980)                  | 112         |
| 4.9  | Hydraulic conductivity functions with responds to volumetric water content of the residual soils predicted by using Van Genutchten's method (1980)       | 113         |
| 4.10 | Field matric suction respond to rainfall distribution at slope without tree during monitoring period of July 2011 to December 2012The rainfall simulator | 115-<br>117 |
| 4.11 | Field matric suction respond to rainfall distribution at Station Slope 1, 2 and 3 during monitoring period of July 2011 to December 2012                 | 119-<br>127 |
| 4.12 | Field matric suction respond to rainfall distribution at Station Flat 1, 2 and 3 during monitoring period of July 2011 to December 2012                  | 129-<br>137 |
| 4.13 | Effective stress failure envelopes and Mohr's circles for sample 1, 2 and 3  | 139         |



|      |  |     |
|------|--|-----|
| 4.14 | Soil Water Characteristic Curve (SWCC) based on gravimetric water content versus suction                     | 140 |
| 4.15 | Apparent shear strength versus suction at low cell pressures (20 and 50 kPa)                                 | 144 |
| 4.16 | Apparent shear strength versus suction at high cell pressures (100 and 200 kPa)                              | 145 |
| 4.17 | Apparent shear strength envelopes with direction of dilation increasing                                      | 146 |
| 4.18 | Matric suction profiles on slope without tree as result of an intense and short rainfall                     | 149 |
| 4.19 | Matric suction profiles on slope 1m from tree as result of an intense and short rainfall                     | 151 |
| 4.20 | Matric suction profiles on slope without tree as result of an antecedent rainfall                            | 152 |
| 4.21 | Matric suction profiles on slope 1m from tree as result of an antecedent rainfall                            | 153 |
| 4.22 | Matric suction profiles on slope without tree as result of prolonged antecedent rainfall                     | 154 |
| 4.23 | Matric suction profiles on slope 1m from tree as result of prolonged antecedent rainfall                     | 155 |
| 5.1  | Matric suction distribution due to rainfall on 18th December 2011, 19th December 2011 and 23rd December 2011 | 162 |
| 5.2  | Matric suction distribution due to rainfall on 31st February 2012, 2nd February 2012 and 4th February 2012   | 162 |
| 5.3  | Field matric suction profiles directly 1m from tree (Station slope 1)  | 167 |

|      |  |     |
|------|--|-----|
| 5.4  | Field matric suction profiles directly 2m from tree (Station slope 2)  | 168 |
| 5.5  | Field matric suction profiles directly 4m from tree (Station slope 3)  | 169 |
| 5.6  | Field matric suction profiles at toe of slope without tree   | 170 |
| 5.7  | Ranges of measurement matric suction at 1m from tree (Station Slope 1) from 25th December 2011 to 6th January 2012 | 171 |
| 5.8  | Ranges of measurement matric suction at 2m from tree (Station Slope 2) from 25th December 2011 to 6th January 2012 | 172 |
| 5.9  | Ranges of measurement matric suction at 4m from tree (Station slope 3) from 25th December 2011 to 6th January 2012 | 172 |
| 5.10 | Ranges of measurement matric suction at at toe of slope without tree from 25th December 2011 to 6th January 2012   | 173 |
| 5.11 | Field matric suction results on 24 December 2011 at Station Slope and Slope without tree                           | 174 |
| 5.12 | Field matric suction results on 24 December 2011 at Station Flat and Slope without tree                            | 174 |
| 5.13 | Field matric suction on 2nd January 2012 at Station Slope and Slope without tree                                   | 175 |
| 5.14 | Field matric suction on 2nd January 2012 at Station Flat and Slope without tree                                    | 176 |
| 5.15 | Field matric suction on 6th January 2012 at Station Slope and slope without tree                                   | 177 |
| 5.16 | Field matric suction on 6th January at Station Flat and slope without tree   | 177 |

|      |  |     |
|------|--|-----|
| 5.17 | Finite element mesh of measured slope geometry with tree at toe of slope   | 180 |
| 5.18 | Matric suction (kPa) contour on 2nd January 2012   | 181 |
| 5.19 | Matric suction (kPa) contour on 6th January 2011   | 182 |
| 6.1  | Non-linear variation of shear strength relative to matric suction for tropical residual soil (Toll <i>et al.</i> , 2000)   | 192 |
| 6.2  | Illustrating the effect of desaturated and shear strength, relationship between soil-water characteristic curve and shear strength versus matric suction envelope (Gan and Fredlund, 1996) | 193 |
| 6.3  | Non-linear in failure envelope with several $\phi^b$ value on the shear strength versus matric suction plane (Fredlund <i>et al.</i> , 1987)   | 194 |
| 6.4  | Non-linearity in the failure envelope on the apparent strength versus suction plane Comparison between   | 195 |
| 6.5  | Forces acting on a slice through a sliding mass with a circular slip surface, modified after Fredlund and Rahadjo (1993)   | 197 |
| 6.6  | Identification of the critical slip surface using commercial software (SLOPE/W)  | 201 |
| 6.7  | Detail of slope geometry with slip surface and location of slices  | 202 |
| 6.8  | Variation of FOS with matric suction   | 204 |
| 6.9  | Matric suction (kPa) variations with critical slip surface and slices on slope at Faculty Electrical Engineering   | 205 |
| 6.10 | Moisture content profiles at distance 1 m from tree (Station slope 1)  | 206 |
| 6.11 | Moisture content profiles at distance 2 m from tree (Station slope 2)  | 207 |
| 6.12 | Moisture content profiles at distance 4 m from tree (Station slope 3)  | 207 |

|      |   |         |
|------|---|---------|
| 6.13 | Matric Suction (kPa) encounter at the base of the slice (refer to figure 6.9)   | 208     |
| 6.14 | Factor of safety versus time for slopes with and without tree at toe (July 2011-December 2012)  | 209-210 |
| 7.1  | Comparison of nonlinear failure envelope for the soil at study area   | 217     |
| 7.2  | Progressive development of matric suction during drying periods at 1m from tree   | 218     |
| 7.3  | Progressive development of matric suction during drying periods at 2m from tree   | 219     |
| 7.4  | Progressive development of matric suction during drying periods at 4m from tree   | 219     |
| 7.5  | Simulated (period time 21 days) and measured matric suction profile from 20th July 2012 to 11th August 2012 at 1 m from tree                                | 228     |
| 7.6  | Simulated (period of time 21 days) and measured matric suction profile from 20th July 2012 to 11th August 2012 at 2 m from tree                             | 229     |
| 7.7  | Simulated (period of time 21 days) and measured matric suction profile from 20th July 2012 to 11th August 2012 at 4 m from tree                             | 229     |
| 7.8  | Contour of matric suction (kPa) in the vicinity of <i>Acacia mangium</i> tree at toe of slope (a) numerical simulation (b) actual field measurement results | 230     |

## 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            |

**LIST OF APPENDICES**

| <b>APPENDIX</b> | <b>TITLE</b>   | <b>PAGE</b> |
|-----------------|--|-------------|
| A               | Summary of Consolidated Isotropic Undrained (CIU) Test Result          | 262         |
| B               | Unconsolidated Undrained Test Results                                  | 265         |
| C               | Field Monitoring Data at Slope Of Faculty Of Electrical Engineering    | 286         |
| D               | Calculation Of FOS Related To Saturated Slope                          | 300         |
| E               | Calculation Of FOS With Variation of Matric Suction and $\phi^b$ Angle | 301         |
| F               | Calculation Of FOS Without and With Tree At Toe                        | 305         |
| G               | List Of Publications   | 319         |