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Modelling of influence of matric suction induced by native vegetation on sub-soil improvement

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**MODELLING OF INFLUENCE OF MATRIC SUCTION INDUCED BY
NATIVE VEGETATION ON SUB-SOIL IMPROVEMENT**

A thesis submitted in fulfilment of the requirement
for the award of the degree

Doctor of Philosophy

from

University of Wollongong

by

Behzad Fatahi, BSc Eng (Hons), MSc Eng, CPEng

School of Civil, Mining and Environmental Engineering
Faculty of Engineering
2007

CERTIFICATION

I, Behzad Fatahi, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Department of Civil Engineering, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualification at any other academic institution.

Behzad Fatahi
October 2007

I don't really understand this veranda allowing nine passages to one another
I don't really know this magic painter

I have an ailment and need remedy, but Galen says
'I don't really know this ailment and its remedy'

Jalal-ud-din Rumi , Molana
(Our Master)

Sincerely Dedicated to

My Father and Mother

Bahram & Monir

ABSTRACT

Bioengineering including native vegetation is an ancient method of improving the stability of slopes. In modern railway engineering, this technique is re-captured for increasing the soil stiffness and shear strength of sub-grade beneath rail tracks. Currently this practice has become increasingly popular in Australia for stabilising railway corridors built over expansive clays and compressive soft soils. The tree roots provide three stabilising functions: (a) reinforcement of the soil, (b) dissipation of excess pore pressures and (c) establishing sufficient matric suction to increase the shear strength.

The main focus of this research is to investigate the effects of vegetation on soil matric suction, ground settlement and lateral movement (radial consolidation). A mathematical model for the rate of root water uptake has been developed based on the root growth rate and considering ground conditions, type of vegetation and climatic parameters. The three independent features in the root water uptake model considered in detail are soil suction, root distribution, and potential transpiration. In order to establish a rigorous analysis for estimating the actual transpiration or root water uptake, the above mentioned factors have been quantified through relevant equations to develop the proposed root water uptake model.

A two dimensional finite element approach based on ABAQUS has been employed to solve the transient coupled flow and deformation equations. The proposed root water uptake model has been implemented in the coupled analysis by introducing a sink term as a subroutine in the finite element analysis. The finite element mesh can be constructed using partially/fully saturated soil elements, representing the salient aspects of unsaturated permeability and the soil water characteristic curve. The model formulation is based on the general effective stress theory of unsaturated soils. Based on this proposed model, the distribution of the matric suction profile adjacent to the tree has been numerically analysed. To validate the model, an array of field measurements conducted at Miram site in Victoria, Australia and the data have been compared with the numerical predictions. The predicted results calculated using the soil, plant, and atmospheric parameters contained in the numerical model, compared favourably with the field and the associated laboratory measurements, justifying the assumptions upon which the model has been developed. The

numerical analysis encompassing the developed root water uptake model can reasonably predict the region of maximum matric suction (away from the tree trunk axis), which has been consistent with the field measurements.

Moreover, field measurements taken from the previously published literature have been compared with the numerical predictions. It is found that given the approximation of the assumed model parameters, the agreement between the predicted results and field data is still promising. The influence of different parameters on the maximum rate of root water uptake is investigated through parametric and sensitivity analyses. In addition, the rate of selected parameters such as potential transpiration and its distribution, suction at wilting point, the coefficient of permeability and the distribution of root length density have been studied in detail. The findings of this study confirm that four key parameters, including permeability, wilting point suction, density and distribution of the root length, and the rate of potential transpiration should be estimated or measured accurately in order to predict the behaviour of clayey soils near tree roots.

The action of a single tree on improving the soil behaviour has been compared to a vertical drain with applied suction (vacuum pressure). It is seen that root water uptake and associated matric suction is analogous to a prefabricated vertical drain with vacuum preloading, and the lateral inward displacements simulate the radial consolidation process of prefabricated vertical drains. If a pattern of trees can be grown systematically along rail corridors, this may offer a cheaper and more environmentally attractive solution to vertical drains in the long-term.

The results of this study provide a valuable and a relatively accurate mean to estimate the influences of vegetation on ground. The numerical model developed herein offers practicing geotechnical engineers an effective tool for designing structures on vadose zones containing vegetation. It is desirable to consider the influence zone of tree roots and the improved soil properties in modern geotechnical designs, benefiting from native vegetation.

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LIST OF PUBLICATIONS AND AWARDS

The following publications are original work from this PhD thesis.

a. Refereed Journals

1. Indraratna B., **Fatahi B.** and Khabbaz M. (2006). "Numerical Analysis of Matric Suction Effects Induced by Tree Roots", *Geotechnical Engineering*, ICE, UK, 159, No.2, 77-90.
2. **Fatahi B.** and Indraratna B., (2006). "A Case Study and Pilot Parametric Study on the Effect of Root-Based Suction on Ground Behaviour", *Geotechnical Engineering*, ICE, UK, (Submitted).

b. Book Chapter

1. Indraratna B., **Fatahi B.** and Khabbaz M.H., (2007). "Finite Element Modelling of Soil-Vegetation Interaction", *Theoretical and Numerical Unsaturated Soil Mechanics*, Schanz, T. (Ed.), Springer Verlag, 211-224

c. Peer-Reviewed Conferences

1. Indraratna, B. and **Fatahi, B.** (2006). Sensitivity analysis to examine tree root effectiveness in soft ground stabilisation. Proceedings of 6th European Conference on Numerical Methods in Geotechnical Engineering, Graz, Austria (6-8 September 2006) (Edited by H.F Schweiger), pp. 735-742
2. **Fatahi B.**, Indraratna B., and Khabbaz H. (2006). "Modelling Of Soft Soil Improvement Induced By Tree Root Suction", Proceedings of International Symposium of Soft Soil Engineering, Australian Geomechanics Society, Sydney, 155-166
3. Indraratna B., **Fatahi B.** and Khabbaz M.H., (2006). "A Numerical Parametric Study on Matric Suction Effects Induced by Tree Roots on Ground Conditions", Proceedings of Geo Congress 2006, Geo Institute, ASCE, 26 Feb - 2 March, Georgia, Atlanta, USA, (CD-R)

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TABLE OF CONTENT

ABSTRACT	IV
ACKNOWLEDGEMENT	VI
PUBLISHED WORK	VII
TABLE OF CONTENT	IX
LIST OF FIGURES	XIV
LIST OF TABLES	XX
LIST OF SYMBOLS	XXI
1. INTRODUCTION	
1.1 General	1
1.2 Description of Problem	2
1.3 Application of Native Vegetation for Ground Modification	3
1.4 Objectives and Scope of Study	4
1.5 Organisation of the Thesis	6
2. INFLUENCE OF VEGETATION ON GROUND CONDITIONS - LITERATURE REVIEW	
2.1 General	8
2.2 Hydrological Features	10
2.3 Transpiration	11
2.3.1 Measuring Transpiration`	13
2.3.2 The Influence of Humidity, Temperature, and Wind Speed on Transpiration Rate	14
2.3.3 Influence of Leaf Area on Transpiration Rate	16
2.4 Tree Physiology	17
2.5 Advantages of Bioengineering	19
2.6 Root Reinforcement Effect	21
2.7 Root Length Density Measurements	22

2.7.1	Excavation	23
2.7.2	Monolith	23
2.7.3	Auger	23
2.7.4	Profile Wall	24
2.7.5	Glass Wall	24
2.7.6	Radioactive Tracers	24
2.8	Root Development	24
2.8.1	Maximum Root Depth	25
2.8.2	Horizontal Root Spread	25
2.9	Tree Root Water Uptake	26
2.9.1	Soil Conditions	27
2.9.1.1	Effect of Soil Suction	27
2.9.1.2	Effect of Soil Hydraulic Conductivity	28
2.9.1.3	Effect of Soil shear strength	31
2.9.2	Tree Specifications	32
2.9.2.1	Effect of Root Length Density	32
2.9.2.2	Effect of Relative Proportion of Active Roots	34
2.9.2.3	Effect of Leaf Area	34
2.9.3	Effects of Atmospheric Conditions	34
2.9.3.1	Potential Transpiration Rate	34
2.10	Soil Suction Measurement	35
2.11	Tree – Ground Interaction	43
2.12	Predictive Models	46
2.13	Summary	50

3. GOVERNING EQUATIONS OF TREE ROOT WATER UPTAKE

3.1	General	52
3.2	Influence of Hydrological Features	53
3.3	Unsaturated Flow Equation Considering Root Suction	54
3.4	Root Water Uptake Model	57
3.5	Parametric Study of the Initial Rate of Root Water Uptake	69

3.6	Sensitivity Analysis of the Model Parameters	73
3.7	Analytical Solution	75
3.8	Summary	82
4.	NUMERICAL ANALYSIS OF COUPLED FLOW AND DEFORMATION EQUATIONS OF UNSATURATED SOILS CONSIDERING ROOT BASED SUCTION	
4.1	General	85
4.2	Effective Stress Equation of Unsaturated Soils	86
4.3	Coupled Flow and Deformation Governing Equations	89
4.3.1	Deformation model	89
4.3.2	Liquid Flow	92
4.3.3	Gas Flow	93
4.4	Application of ABAQUS Finite Element Code	97
4.5	Flowchart of Numerical Analysis	100
4.6	Summary	102
5.	FIELD AND LABORATORY EXPERIMENTS SUPPLEMENTED WITH NUMERICAL ANALYSIS – CASE STUDY ONE	
5.1	General	103
5.2	Site Location and Geological Conditions	104
5.3	Climate and Hydrology	104
5.4	Tree Specifications	107
5.5	Site Characteristics, Arrangement, and Measurements	107
5.6	Root Distribution	117
5.7	Numerical Modelling	122
5.8	Stage one – Field Measurements in May 2005	130
5.9	Stage two – Field Measurement in April 2006	135
5.10	Summary	138

6. MODEL VERIFICATION

6.1	General	140
6.2	Evaluation of the Numerical Model	140
6.3	Further Verification of the Proposed Root Water Uptake Model	146
6.3.1	Case study 1	146
6.3.2	Case study 2	153
6.3.3	Case Study 3	157
6.4	Summary	163

7. PARAMETRIC STUDY AND SENSITIVITY ANALYSIS

7.1	General	165
7.2	Parametric Study and Sensitivity Analysis for Case 1	165
7.2.1	Effect of Elapsed Time	166
7.2.2	The Effect of the Rate of Potential Transpiration	168
7.2.3	The Effect of Maximum Root Density	170
7.2.4	The Effect of Wilting Point Value	171
7.2.5	The Effect of Saturation Permeability	172
7.2.6	The Effect of Vertical and Horizontal Root Density Distribution Factors	174
7.2.7	The Effect of Potential Transpiration Distribution Factor	176
7.2.8	Sensitivity Analysis of Ground Settlement	176
7.3	Parametric Study and Sensitivity Analysis for Case 2	178
7.3.1	A Description of the Reference Problem for Case 2	178
7.3.2	An Analysis of the Reference Problem	181
7.3.3	The Effect of Elapsed Time	182
7.3.4	The Effect of the Rate of Potential Transpiration	185
7.3.5	The Effect of Maximum Root Density	188
7.3.6	The Effect of Wilting Point Value	189
7.3.7	The Effect of Saturation Permeability	192
7.3.8	Effect of Vertical Root Density Distribution Factor	193
7.3.9	The Effect of Horizontal Root Density Distribution Factor	195
7.3.10	The Effect of Potential Transpiration Distribution Factor	197

7.3.11 A Sensitivity Analysis of Ground Settlement	199
7.4 Summary	200
8. PRACTICAL APPLICATIONS	
8.1 General	202
8.2 Numerical Modelling	203
8.3 Results	207
8.4 Summary	215
9. CONCLUSIONS AND RECOMMENDATIONS	
9.1 General Summary	216
9.2 Specific Observations	218
9.2.1 Development of a New Root Water Uptake Model	218
9.2.2 Numerical Modelling of the Interaction between Tree and Ground	218
9.2.3 Field and Laboratory Programs	220
9.2.4 Case History Analysis	220
9.2.5 Parametric Study and Sensitivity Analysis	222
9.3 Recommendations for Future Work	223
BIBLIOGRAPHY	224
APPENDIX A: FORTRAN Subroutines	237
APPENDIX B: Borehole Logs	246
APPENDIX C: Core Box Photographs	257

LIST OF FIGURES

Figure 1.1 (a) Two dimensional vertical view of the root zone and the influence zone of a tree (b) a schematic horizontal cross section	2
Figure 2.1 A demonstration of xylem sap exudation due to root pressure in tomato. Photograph was taken 10minutes after excising the stem of a well-watered plant (Hopkins, 1999)	18
Figure 2.2 water uptake – moisture content relationship (After Feddes et al., 1976)	27
Figure 2.3 Root development within the sandy soil, compacted below 25 cm and to the right of the plant axis (after Clausnitzer and Hopmans, 1994)	32
Figure 2.4 Comparison between measured and predicted soil temperature in 4 years duration (after Pomper et al., 1990)	37
Figure 2.5 Relationship between pore radius, and matric suction (after Fredlund and Raharadjo, 1993)	38
Figure 2.6 Trees planted along Railway lines, Coalcliff, NSW, Australia	43
Figure 2.7 Field measurements of total suction at Miram site in July 2004 (Potter, 2006)	44
Figure 2.8 Recommended total suction profile for (a) single large spotted gums (Depth/Height<0.5) and (b) a group of large spotted gums (Depth/Height <0.8) (Jaksa et al. 2002)	46
Figure 2.9 Simulated versus measured soil volumetric water contents around the almond tree employing HYDRUS-3D (Vrugt et al., 2001)	49
Figure 3.1 Soil system including hydrogeological features	53
Figure 3.2 Schematic sketch of soil-plant-atmosphere system, (a) transpiration (b) soil-plant-atmosphere interaction and (c) active and main roots	58
Figure 3.3 Schematic sketch of soil-plant-atmosphere system	60
Figure 3.4 Variation of normalised root zone size and maximum root density with normalised time	62
Figure 3.5 Soil suction factor (modified after Feddes et al., 1978)	67
Figure 3.6 Initial distribution of root water uptake rate	69
Figure 3.7 Effect of α on RWU_{max}	70
Figure 3.8 Effect of k_1 and k_2 on RWU_{max}	71
Figure 3.9 Effect of k_3 on RWU_{max}	71
Figure 3.10 Effect of k_4 on RWU_{max}	72
Figure 3.11 Effect of β and T_p on RWU_{max}	72

Figure 3.12 Results of the sensitivity analysis for RWU_{\max}	74
Figure 3.13 soil media considering conical root zone shape	78
Figure 3.14 Flow chart to calculate root water uptake rate as the sink term in the moisture flow equation	84
Figure 4.1 An illustration of three phases of porous media	86
Figure 4.2 Schematic soil water characteristic curve	88
Figure 4.3 Flow chart of approximate solution of coupled-flow deformation governing equation	101
Figure 5.1 Location of the site for the geotechnical investigation, Victoria, Australia	104
Figure 5.2 Monthly rainfall data from 2003 until 2006	105
Figure 5.3 Monthly maximum temperature data from 2003 until 2006	106
Figure 5.4 Monthly evaporation rate from 2003 until 2006	106
Figure 5.5 Field work (a) Borehole locations (b) CPT locations	108
Figure 5.6 Geotechnical section of Miram sit	109
Figure 5.7 Soil Particle Size Distribution	111
Figure 5.8 General soil profile and properties at Miram site, VIC, Australia	112
Figure 5.9 Original tube and cut rings	112
Figure 5.10 Profiles of soil properties at Miram site, VIC, Australia	113
Figure 5.11 Profiles of soil properties at Miram site.	114
Figure 5.12 laboratory soil suction measurements (a) pressure plate test, and (b) filter paper method	115
Figure 5.13 Soil water characteristic curves for soil depths of (a) 0-1.5m, (b) 1.5-3.0m, (c) 3.0-4.5m and (d) 4.5-6.0m	116
Figure 5.14 Profile of the distribution of average matric suction near a tree	117
Figure 5.15 Organic Content Distribution in the vicinity of <i>Eucalyptus largiflorens</i> located at Miram, Victoria, Australia	118
Figure 5.16 Relationship between the dry weight and length of active roots of <i>Eucalyptus largiflorens</i>	119
Figure 5.17 (a) plan of trenches (b) trench excavation and (c) picture of excavated trench	120
Figure 5.18 Reinforcing roots of a Black Box tree observed at Miram	121
Figure 5.19 Geometry and boundary conditions of the model	122
Figure 5.20 Actual evaporation – soil suction relationship (modified after Aydin et al., 2005)	123

Figure 5.21 Monthly potential transpiration rate from 2003 until 2006	125
Figure 5.22 Cap model (a) yield surface in principle stress space, (b) yield surface in p-t plane	127
Figure 5.23 Contours of volumetric soil moisture content reduction in vicinity of the tree (a) current numerical analysis results, (b) field measurements in May 2005	130
Figure 5.24 Soil matric suction profiles at (a) 2.7m (b) 7.3m (c) 12.5m (d) 17.5m (e) 26.1m (f) 33.6m away from the tree trunk at the eastern side of the trunk in May 2005	132
Figure 5.25 Soil matric suction profiles at (a) 4m (b) 9.6m (c) 19.7m (d) 29.7m away from the tree trunk at the western side of the trunk in May 2005	133
Figure 5.26 Model predictions for the contours of vertical displacement	133
Figure 5.27 Predictions for the contours of lateral displacement	134
Figure 5.28 Lateral displacement vectors	135
Figure 5.29 Profiles of the soil matric suction in April 2006 shown at (a) 5m (b) 10m (c) 30m away from the tree at the western side	136
Figure 5.30 Ground settlement in the middle of April 2006 at various depths	137
Figure 6.1 The geometry and boundary conditions of the model	141
Figure 6.2 Soil water characteristic curve (after Fredlund and Hung, 2001)	142
Figure 6.3 Initial matric suction (kPa) and matric suction (kPa) profile after 1 month	143
Figure 6.4 Initial matric suction (kPa) and matric suction (kPa) profile after 6 months	144
Figure 6.5 Initial matric suction (kPa) and matric suction (kPa) profile after 1 year	144
Figure 6.6 Contours of soil matric suction (kPa) in the vicinity of a row of trees (a) Fredlund and Hung (2001), and (b) current finite element analysis	145
Figure 6.7 Contours of vertical displacement (mm) near a row of trees (a) Fredlund and Hung (2001), and (b) current finite element analysis	145
Figure 6.8 The geometry and boundary conditions of case history 1	147
Figure 6.9 the predicted characteristic curve of soil water based on (modified after Zapata et al., 2000)	148
Figure 6.10 Initial matric suction (kPa) profile near the single tree selected.	150
Figure 6.11 A numerical prediction of the change in matric suction against the lateral distance from the trunk after one year of continuous transpiration.	150

Figure 6.12 Field measurements of the changes in total suction against the lateral distance from the trunk (after Jaksa et al., 2002)	151
Figure 6.13 Ground settlement at various depths after one month.	152
Figure 6.14 Ground settlement at various depths after 12 months	152
Figure 6.15 The geometry and boundary conditions of case study	154
Figure 6.16 Predicted soil matric suction at different depths	156
Figure 6.17 Contours of volumetric reduction in soil moisture content (%) near a lime tree (a) Biddle (1983) (b) current finite element	157
Figure 6.18 The geometry and boundary conditions of the FE model, case study 3	159
Figure 6.19 Predicted matric suction profile after five months	161
Figure 6.20 Predicted ground settlement profile at various depths after 5 months.	162
Figure 6.21 Contours of reduced volumetric soil moisture (%) near a Poplar tree, (a) current finite element analysis and (b) Biddle (1998)	162
Figure 7.1 Effect of elapsed time on soil surface settlement	166
Figure 7.2 Matric suction change at a depth of 2m	167
Figure 7.3 The effect of elapsed time on changes to the matric suction under the trunk	167
Figure 7.4 Evolution of soil matric suction (Pa), (a) initial (b) after seven days, (c) one month, (d) two months, (e) four months, and (f) six months.	168
Figure 7.5 The effect of TP on (a) matric suction change at a depth of 1m (b) soil surface settlement	169
Figure 7.6 The Effect of on (a) change of matric suction at a depth of 1m and (b) surface settlement	171
Figure 7.7 The Effect of on (a) change in matric suction at a depth of 1m and (b) surface settlement	172
Figure 7.8 The Effect of permeability on changes in matric suction under a trunk	173
Figure 7.9 Effect of saturation permeability on surface settlement	173
Figure 7.10 The effect of k_1 on changes to the matric suction under the trunk	174
Figure 7.11 The effect of k_1 on surface settlement	175
Figure 7.12 The effect of k_2 on changes to the matric suction at a depth of 1m	175
Figure 7.13 The effect of k_4 on changes to the matric suction under the trunk	176
Figure 7.14 Results of the sensitivity analysis for maximum settlement	177
Figure 7.15 The geometry and boundary conditions of the FE model	179

Figure 7.16 Initial soil matric suction profile	181
Figure 7.17 The matric suction profile in a steady state condition	181
Figure 7.18 A profile of ground settlement at various depths.	182
Figure 7.19 The effect of elapsed time on surface settlement	183
Figure 7.20 The effect of elapsed time on the change in matric suction on the surface	183
Figure 7.21 Change in matric suction at a depth of 2m.	184
Figure 7.22 The effect of elapsed time on change in matric suction under a tree	184
Figure 7.23 Evolution of soil matric suction (Pa), (a) initial (b) after seven days, (c) one month, (d) four months, (e) six months, and (f) twelve months.	185
Figure 7.24 The effect of T_P on change in matric suction under a tree in a steady state condition	186
Figure 7.25 The effect of T_P on change in matric suction at the surface under steady state conditions	186
Figure 7.26 The effect of T_P on change of soil suction at a depth of 2m	187
Figure 7.27 The effect of T_P on surface settlement under steady state conditions	187
Figure 7.28 The effect of maximum root density on change in matric suction under the tree	188
Figure 7.29 The effect of Maximum root length density on change in matric suction in a 4m radius from the tree	189
Figure 7.30 The effect of ρ_r on change of matric suction 4m away from the tree	190
Figure 7.31 The effect of ρ_r on change of matric suction at the surface	190
Figure 7.32 The effect of ρ_r on surface settlement	191
Figure 7.33 Effect of ρ_r on change of matric suction at a depth of 2m	191
Figure 7.34 The effect of ρ_r on change of matric suction under the tree	192
Figure 7.35 The effect of ρ_r on change of matric suction at a depth of 2m	192
Figure 7.36 The effect of ρ_r on surface settlement	193
Figure 7.37 The effect of k_1 on change of soil matric suction at a depth of 2m	194
Figure 7.38 The effect of k_1 on change of soil matric suction 4m away from the tree	194
Figure 7.39 The effect of k_1 on change of soil matric suction under the tree	195
Figure 7.40 The effect of k_1 on surface settlement	195
Figure 7.41 The effect of k_2 on change of soil matric suction at a depth of 2m	196

Figure 7.42 The effect of k_2 on change of soil matric suction 4m away from the tree	196
Figure 7.43 The effect of k_2 on change of soil matric suction on the surfac	197
Figure 7.44 The effect of k_2 on surface settlement	197
Figure 7.45 The effect of k_4 on change of soil matric suction at a depth of 2m	198
Figure 7.46 The effect of k_4 on change of soil matric suction 4m away from the tree	198
Figure 7.47 Results of the sensitivity analysis for maximum ground settlement	199
Figure 8.1 Geometry and boundary conditions of the finite element model	203
Figure 8.2 Contours of soil matric suction induced by (a) tree root water uptake, and (b) vacuum preloading (100kPa)	208
Figure 8.3 Contours of ground settlements in top 5 m of soil layer induced by Black Box tree transpiration	209
Figure 8.4 Contours of ground settlements in top 5 m of soil layer induced by PVDs with 100kPa Vacuum Pressure	210
Figure 8.5 Time-Settlement curves during consolidation prior to and after the application of the train load.	212
Figure 8.6 Soil Undrained Shear Strength under the track Centre Line after Different	214
Figure 9.1 Flowchart of the predictive procedure of the proposed model	219

LIST OF TABLES

Table 2.1 Description of some hydrological features	12
Table 2.2 The energy budget for a typical mesophyte leaf (from Hopkins 1999)	13
Table 2.3 Water vapour pressure (kPa) in air is a function of temperature and varying degrees of saturation. (after Hopkins, 1999)	15
Table 2.4 Tree size classification (Warbington et al.,1998)	17
Table 2.5 Different root water uptake reduction factors suggested by different researchers	29
Table 2.6 Influence of Root density on root water uptake rate	33
Table 2.7 Soil suction measurement devices and their details	40
Table 3.1 Parameter values used to calculate initial rate of root water uptake	68
Table 3.2 Sensitivity of RWU_{max} to the incorporated parameters	75
Table 5.1 Average soil permeability at the Miram site, VIC, AUstralia	114
Table 5.1 Parameters of interaction between tree and ground of a Black Box tree at Miram	122
Table 5.2 Parameter values used in the finite element analysis	130
Table 6.1 Parameters applied in the finite element analysis of case study 1	146
Table 6.2 Parameter values assumed in the finite element analysis of case study 1	149
Table 6.3 Parameters applied in the finite element analysis of case study 2	154
Table 6.4 Parameter values assumed in the finite element analysis of case study 2	155
Table 6.5 Parameters applied in the finite element analysis of the case study	158
Table 6.6 Parameter values assumed in the finite element analysis of the case study	160
Table 7.1 Sensitivity of the maximum settlement to some model parameters	178
Table 7.2 The initial assumed parameter values in the numerical parametric study	180
Table 7.3 Sensitivity of the maximum settlement to some of the parameters	200
Table 8.1 Parameter values assumed in the finite element analysis of the case study	207

LIST OF SYMBOLS

A	experimental coefficients
A_d	amplitude of the sine wave
a	experimental constant
a_{11}	apparent compressibility of water
a_{12}	coupling factors relating microscopic pore water deformations
a_{21}	coupling factors relating microscopic pore air deformations
a_{22}	apparent compressibility of air
B	empirical constant
b	experimental constant
b_1	experimental coefficient
b_2	experimental coefficient
$b(z)$	empirical function representing the geometry of flow
C_a	concentration of the diffusing air
C_c	compression index
C_s	swelling index
C_{k-c}	Koezy-Carman empirical coefficient
$[C]_{8 \times 4}$	coupling matrix between flow and deformation
c	experimental coefficients.
c'	effective cohesion of the soil
c_f	compressibility coefficient of fluid
c_m	compressibility coefficient of soil with respect to suction
c_p	specific heat capacity of air at constant pressure
$D(t)$	drainage rate
$D(\theta)$	diffusivity
D_a	vapour pressure deficit of air

D_i^*	transmission coefficient for the air phase
D_i	coefficient of diffusion
$d(r, z, t)$	average root diameter at point (r, z) at time t
d	intersection of conus yield surface with the t-axis or mate
$d_0(t)$	average root diameter directly beneath the trunk
de^{el}	change of void ratio in the element
dV	small volumetric change
dp	mean effective stress change
E	drained initial modulus of deformation
$E(t)$	evaporation rate
E_A	atmospheric drying power function
E_p	potential evaporation
ET_p	potential evapotranspiration
$[E]_{8 \times 8}$	conventional stiffness matrix
e	void ratio
F_c	compression cap yield surface
F_i	body force per unit volume
$F_I(t)$	inflow of ground water (lateral flow)
F_O	outflow of ground water (lateral flow)
F_s	pressure dependent, perfectly plastic shear failure surface,
$F(T_p(t))$	potential transpiration factor
$f(\beta)$	root density function
$f(\psi)$	soil suction reduction factor
$f_1(z)$	function of the initial distribution of moisture content
f_i	fractional area of each leaf in terms of the total leaf area
G	shear modulus or soil heat flux
$G(\beta)$	root density distribution function

G_s	nonassociated flow potential of the shear surface
G_c	associated flow potential of the cap
g	plastic potential.
H	Henry's constant ($H \cong 0.02$)
H_{root}	effective water potential in the root at the soil surface
$[H_1]_{4 \times 4}$	matrix of material properties
$[H_2]_{4 \times 4}$	matrix of material properties
h	hardening variable
$h(z)$	pressure head in the soil
h_p	water potential of roots
$h_r(z)$	pressure head at the soil-root interface
h_s	water potential of soil
I	quantity of water entering the soil system (Input),
$I_T(t)$	effective interception
$(I_s)_{u_i}$	sensitivity index of parameter u_i
J_{ai}	mass rate of air diffusing across a unit area,
K	shape parameter of the conus yield surface
k	hydraulic conductivity
k_1	coefficient to determine the change of β with depth
k_2	coefficient to determine change of β with lateral distance
k_3	experimental coefficient
k_4	experimental coefficient
k_{ai}	permeability coefficient for air
k_p	pan coefficient
k_r	experimental constant
k_s	coefficient of permeability at saturation
$L(z)$	length of roots per unit soil volume

$L(t)$	confining distance of roots below the soil surface
$LAI(t)$	leaf area index
$l(t)$	active root zone depth at time t
M	slope of critical state line
$[M]_{4 \times 4}$	conventional mass matrix
m_1	experimental coefficients
m_a	mass of air in the soil element
n	intensive quantity (per unit volume), porosity or constant
O	quantity of water leaving the soil system (Output)
$P(0)$	external load on the upper surface
$P(t)$	percolation rate
P	absolute pressure
P_r	coefficient to estimate the point of the maximum root density
P_z	coefficient to estimate the point of the maximum root density
$PRES$	root resistance term
p	equivalent pressure stress
p'	mean effective stress
p_0	initial mean effective stress
p_b	compression yield stress
p_c	pre-consolidation pressure
q	von Mises equivalent stress
R	universal (molar) gas constant
R_a	root area ratio
R_{a0}	root area ratio exactly underneath the trunk
R_c	flow coefficient in the plant root system
R_{roots}	hydraulic resistance of the roots
R_n	net radiation
$R_{n,i}$	net radiation flux density absorbed by each leaf

R_{SL}	effective hydraulic resistance to water flow from for leaves
R_{soil}	resistance to water flow in the soil
$RDF(z)$	proportion of total active roots in depth increment Δz
RWU_{max}	maximum rate of root water uptake
$r_{max}(t)$	maximum lateral distance of root zone at time t
$r_{max.f}$	maximum possible lateral distance of root zone
$r_{a,i}$	boundary layer resistance of each leaf
$r_{s,i}$	stomatal resistance of each leaf
$S(z,t)$	salt (osmotic) potential soil osmotic head
$S(x, y, z, t)$	root water uptake at point (x, y, z) at time t
S_0	specific surface area per unit volume of particles
S_{act}	specific surface of the active part of the roots
S_e	effective degree of saturation
S_{max}	maximum rate of root water uptake
S_r	degree of saturation
$(S_r)_{res}$	residual degree of saturation
$SI(t)$	supplemental irrigation rate in the soil system
SR	surface runoff
SR_I	input surficial flow to soil system
SR_O	output surficial flow from soil system
s	slope of saturation vapour pressure
T	absolute temperature (K)
$T(t)$	transpiration rate at time t
T_i	tensile strength of root
T_j	potential transpiration rate on the j th day
$T_p(t)$	potential transpiration rate at time t

T_{p0}	potential evaporation rate at a reference point
\bar{T}_p	average potential transpiration rate per unit area of ground
T_r	relative root tensile strength contribution
$T_r(t)$	potential transpiration rate per unit leaf area
\bar{T}_r	average potential transpiration rate per unit leaf area
T_s	water surface tension
t	time or deviatoric stress
t_d	time lag between the peak yearly air and soil temperatures
t_f	time that tree growth
\vec{U}	flow velocity vector
u_a	air pressure
u_i	variable affecting the rate of root water uptake
u_{atm}	atmospheric pressure
u_w	water pressure
u_{w0}	specific volume of water
\bar{u}_v	partial pressure of pore-water vapour
V	volume of soil element
V_w	volume of water within the soil element
v_{ai}	velocity of air flow through soils
W	dimensionless weighted function or amount of water in soil
W_0	initial amount of water content in the soil system
X_m	maximum rooting length in the x direction
x_1	orthogonal coordinate direction
x_2	orthogonal coordinate direction
x_3	orthogonal coordinate direction
Y_m	maximum rooting length in the y direction

Z_m	maximum rooting length in the z direction
$Z(t)$	rate of input water to the soil system
z	depth below soil surface
z_{\max}	maximum depth of root zone
z_{rj}	rooting depth at j th day
$z_{\max}(t)$	maximum depth of root zone at time t
$z_{\max.f}$	maximum possible root zone depth

Greek Letters

α	shape parameter of the transition yield surface.
α_1	coefficient relating to the rate of root water uptake
α_T	coefficient depending on the transpiration rate
$\beta(x, y, z)$	root length density at point (x, y, z)
$\beta_{\max}(t)$	maximum root density at time t
β'	slope of conus yield surface at p-t plane
β_0	root length density at ground surface just under the tree trunk
χ	effective stress parameter attaining
ΔC	apparent cohesion due to tree roots
Δl	typical element dimension
ΔS	changes in surface storage (increase is positive)
Δx	distance between the plant roots
ΔW	changes in the amount of water in the soil system
ΔL	losses
δ	parameter chosen to satisfy the mass balance equation
δ_{ij}	Kronecker's delta
ε_{ij}	total deformation of the soil skeleton
ε_{ij}^e	elastic components of the soil skeleton strain
ε_{ij}^p	plastic components of the soil skeleton strain

Φ	total potential or hydraulic head
Φ_s	the total soil water potential,
Φ_L	total leaf water potential
ϕ	osmotic coefficients or plastic multiplier,
ϕ_{plant}	hydraulic head in the plant at the base of the stem
ϕ_{soil}	total hydraulic head of the soil as a function of depth
$\phi_x(t)$	water potential of the root xylem
ϕ_w	volumetric water content
ϕ'	effective angle of internal friction of the soil,
γ	unit weight of the fluid or psychrometric constant
η	amount of property per unit mass
Γ	organic content of the soil matrix
Γ_{max}	maximum percentage of the organic content
λ	slope of consolidation curve or soil water characteristic curve
λ_1	first root of the polynomial equation
λ_2	second root of the polynomial equation
μ	viscosity of the fluid
Ω	overburden pressure
$\hat{\Theta}_1^*$	first solution of the homogeneous differential equation
$\hat{\Theta}_2^*$	second solution of the homogeneous differential equation
$\overline{\hat{\Theta}}^*$	particular solution of non-homogeneous differential equation
θ	volumetric water content or time weight factor or lode angle
θ_{an}	moisture content at anaerobiosis point
θ_{ave}	annual average soil temperature
θ_d	minimum moisture content when $S = S_{max}$
θ_{sat}	saturate moisture content
θ_w	wilting point moisture content

ρ	density
ρ_a	air density
ρ_w	water density
σ_{ij}	total stress in the porous medium at the point
σ'_{ij}	effective stress of a point on a solid skeleton
v_w	magnitude of the velocity of the pore fluid
ν	number of ions from one molecule of salt
ν	drained Poisson's ratio of the soil structure
ω_0	initial water content of the active root zone
ω_v	molecular mass of water vapour
ζ	molecular weight of the air mass
ψ	matric suction
ψ_w	soil suction at wilting point
ψ_{an}	soil suction at anaerobiosis point
ψ_d	highest value of ψ at $S = S_{\max}$
ψ_e	air entry matric suction
ψ_m	matric suction
ψ_r	root suction generated by the plant
ψ_0	soil suction from which the transpiration rate starts to diminish
$\bar{\psi}$	average value of ψ in the depth interval
ψ_π	osmotic suction
∇	divergence vector