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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 6<sup>th</sup> 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)

4. Indraratna B., **Fatahi B.** and Khabbaz M.H., (2006). “Numerical Prediction of Vadose Zone Behaviour Influenced by Vegetation”, Proceedings of the 4<sup>th</sup> International Conference of Unsaturated Soils, ASCE, April 2- 5, Carefree Resort & Villas, Carefree, Arizona, USA, 2256-2267
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1. Young Railway Engineer of the Year 2007, Railway Technical Society of Australasia (RTSA), Engineers Australia
2. First Prize for Geotechnical Research Contributions at the Young Geotechnical Engineers presentations held at Australian Geomechanics Society, the Institution of Engineers Australia, 2006, Sydney
3. The prize winner at University of Wollongong's Higher Degree Research Student Conference 2005 in the category of “Frontier Technologies for Building and Transforming Australian Industries”

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## 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 $\beta$ with depth
$k_2$	coefficient to determine change of $\beta$ 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 $\Delta z$
$RWU_{max}$	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***

$\alpha$	shape parameter of the transition yield surface.
$\alpha_1$	coefficient relating to the rate of root water uptake
$\alpha_T$	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 $t$
$\beta'$	slope of conus yield surface at p-t plane
$\beta_0$	root length density at ground surface just under the tree trunk
$\chi$	effective stress parameter attaining
$\Delta C$	apparent cohesion due to tree roots
$\Delta l$	typical element dimension
$\Delta S$	changes in surface storage (increase is positive)
$\Delta x$	distance between the plant roots
$\Delta W$	changes in the amount of water in the soil system
$\Delta L$	losses
$\delta$	parameter chosen to satisfy the mass balance equation
$\delta_{ij}$	Kronecker's delta
$\varepsilon_{ij}$	total deformation of the soil skeleton
$\varepsilon_{ij}^e$	elastic components of the soil skeleton strain
$\varepsilon_{ij}^p$	plastic components of the soil skeleton strain

$\Phi$	total potential or hydraulic head
$\Phi_s$	the total soil water potential,
$\Phi_L$	total leaf water potential
$\phi$	osmotic coefficients or plastic multiplier,
$\phi_{plant}$	hydraulic head in the plant at the base of the stem
$\phi_{soil}$	total hydraulic head of the soil as a function of depth
$\phi_x(t)$	water potential of the root xylem
$\phi_w$	volumetric water content
$\phi'$	effective angle of internal friction of the soil,
$\gamma$	unit weight of the fluid or psychrometric constant
$\eta$	amount of property per unit mass
$\Gamma$	organic content of the soil matrix
$\Gamma_{max}$	maximum percentage of the organic content
$\lambda$	slope of consolidation curve or soil water characteristic curve
$\lambda_1$	first root of the polynomial equation
$\lambda_2$	second root of the polynomial equation
$\mu$	viscosity of the fluid
$\Omega$	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
$\theta$	volumetric water content or time weight factor or lode angle
$\theta_{an}$	moisture content at anaerobiosis point
$\theta_{ave}$	annual average soil temperature
$\theta_d$	minimum moisture content when $S = S_{max}$
$\theta_{sat}$	saturate moisture content
$\theta_w$	wilting point moisture content

$\rho$	density
$\rho_a$	air density
$\rho_w$	water density
$\sigma_{ij}$	total stress in the porous medium at the point
$\sigma'_{ij}$	effective stress of a point on a solid skeleton
$v_w$	magnitude of the velocity of the pore fluid
$\nu$	number of ions from one molecule of salt
$\nu$	drained Poisson's ratio of the soil structure
$\omega_0$	initial water content of the active root zone
$\omega_v$	molecular mass of water vapour
$\zeta$	molecular weight of the air mass
$\psi$	matric suction
$\psi_w$	soil suction at wilting point
$\psi_{an}$	soil suction at anaerobiosis point
$\psi_d$	highest value of $\psi$ at $S = S_{\max}$
$\psi_e$	air entry matric suction
$\psi_m$	matric suction
$\psi_r$	root suction generated by the plant
$\psi_0$	soil suction from which the transpiration rate starts to diminish
$\bar{\psi}$	average value of $\psi$ in the depth interval
$\psi_\pi$	osmotic suction
$\nabla$	divergence vector