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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

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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
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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 Geomecahnics 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 4th International Conference of Unsaturated Soils, ASCE, April 2- 5, Carefree Resort & Villas, Carefree, Arizona, USA, 2256-2267

5. **Fatahi, B.,** Indraratna, B. and Khabbaz, H. (2007). Analysing Soft Ground Improvement Caused by Tree Root Suction, GeoDenver, Colorado GeoDenver, Colorado ASCE Special Publication, No. 173 (Edited by Olsen, H.W.) (CD-R)

6. **Fatahi B.,** Indraratna B., and Khabbaz H. (2007). "Enhanced numerical analysis of ground behaviour influenced by tree root suction", Proceedings of Australia and New Zealand Geomechanics Conference, Brisbane, Vol. 1, 142-17

7. **Fatahi B.,** Indraratna B., and Khabbaz H. (2008). "Numerical and Experimental Study of Tree Influence on the Ground", GeoCongress 2008, The Challenge of Sustainability in the Geoenvironment, March 9-12, New Orleans, Louisiana, USA (In Press)

The following awards have been awarded to the author for this research project

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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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
$[C]_{8\times4}$	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
$[E]_{8\times8}$	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
$[H_1]_{4\times4}$	matrix of material properties
$[H_2]_{4\times4}$	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
$[M]_{4\times4}$	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
$\overline{T}_p$	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
$\overline{T}_r$	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
$\overline{u}_v$	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
${\varepsilon_{ij}}^e$	elastic components of the soil skeleton strain
${\varepsilon_{ij}}^p$	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
$\Gamma_{\max}$	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
υ	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
$\overline{\psi}$	average value of ψ in the depth interval
ψ_π	osmotic suction
∇	divergence vector