MODELLING OF SOIL IMPROVEMENT INDUCED BY TREE ROOT SUCTION

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ABSTRACT

Vegetation contributes to weak soil stabilisation through reinforcement of the soil, dissipation of excess pore pressures, and increasing the shear strength by induced matric suction. This paper is concerned with the way vegetation influences soil matric suction, shrinkage, and ground settlement. A mathematical model for the rate of root water uptake that considers ground conditions, type of vegetation and climatic parameters, has been developed. Based on this proposed model, the distribution of moisture and the matric suction profile adjacent to the tree are numerically analysed. Field measurements taken from literature are compared with the authors' numerical model. The predicted results calculated using the soil, plant, and atmospheric parameters implemented in the numerical model, compared favourably with the measured results, justifying the assumptions upon which the model was developed. Furthermore, through the parametric study and sensitivity analysis, the required accuracies of the model parameters are determined. The findings of this study indicate that due to significant reduction in soil moisture content induced by tree roots, the shear strength of the soil will be enhanced.

1 INTRODUCTION

Throughout the world soil conditions on construction sites have become worse than ever due to the overpopulation in the metropolitan areas. These conditions have compelled engineers to construct earth structures, major highways, and railways over expansive clays and compressive clay deposits. According to Nelson and Miller (1992), expansion and shrinkage are the result of changes in the soil water system that disturb the internal stress equilibrium. Retarding evaporation, heavy rainfall, and growth of trees and shrubs are the most important factors which result in a noticeable change in the ground moisture. Trees, shrubs, and grasses deplete moisture from the soil through transpiration.

Australia’s railway network covers a vast area of land over very variable land forms and soil types, and the freight transportation is growing rapidly. The maintenance expenditure is influenced greatly by the large distances covered and the poor quality of the subgrade encountered; therefore, there is pressure to find appropriate methods to reduce the maintenance cost. Following heavy rains, water collection in depressions underneath the rail tracks will result in further track settlement. Continuous ballast resurfacing and replacement and costly track drainage following heavy rains is a large component of the maintenance cost. In design and construction of new railway lines, consideration of an appropriate drainage system is the most viable method to reduce the maintenance cost.

New maintenance observations show when trees are beside railway tracks, their localised undrained failure is minimised. Using native vegetation, to stabilise existing railway corridors built over expansive clays and compressive soft soils, in remote railway lines has become increasingly popular in Australia. Figure 1 shows an example of existence of native trees along railway lines. Properly selected and implemented vegetation, including native trees and shrubs, can reduce soil moisture by root water uptake. Moreover, vegetation can increase the shear strength and stiffness of soil by increasing matric suction and control erosion as a secondary effect.

In modelling of vadose zone behaviour influenced by vegetation, detailed consideration of root water uptake is required to develop a realistic model. Existing models, predicting the effects of vegetation on the ground, consider only the root reinforcement effects or a highly simplified approach for estimating the tree root water uptake. For example, Fredlund and Hung (2001) in their analysis to predict volume change in expansive soils, as a result of vegetation, did not consider the realistic root zone. It was assumed that the root water uptake rate is time-independent, which is not a realistic assumption. The extent and shape of the root system play a major role in determining uptake patterns. Biddle (1998) has reported the most comprehensive field observations for predicting the pattern of soil drying in proximity of trees on clay soils involving 60 different cases. As noted by Gardner (1961) tree root density distribution influences the pattern of moisture redistribution in vicinity of a tree. However, Biddle (1998) did not report the effects of root distribution.

Many attempts (e.g. Cameron, 2001; Jaksa *et al.*, 2002; and Blight, 2005) have been made to establish a relationship between tree roots and soil moisture content. However, the previous experimental investigations could not offer a complete model to include ground properties, vegetation specifications and atmospheric conditions. The main objective of this study is to establish a rigorous formula for estimating root water uptake, and then develop an integrated two-dimensional transient model considering soil water extraction by roots within vadose zone to simulate the ground under the influence of vegetation. The associated mathematical model is implemented in a numerical model to analyse and predict the movement of water in soil. The results are compared with field measurements to verify the numerical predictions. In addition, a sensitivity analysis is carried out to study the influence of the model parameters on the model outputs as well as to identify and evaluate important variables that affect the ground conditions under transpiration.

Figure 1: Trees planted along railway lines, Coalcliff, NSW, Australia

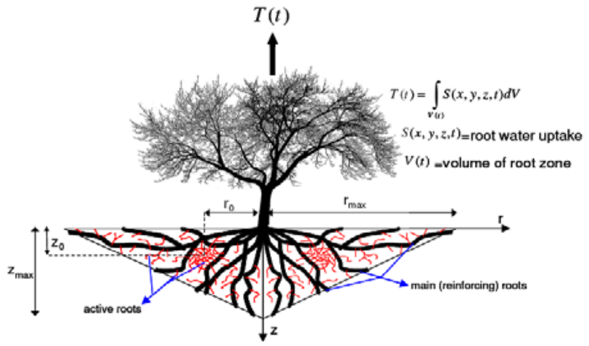

Figure 2: Schematic sketch of soil-plant-atmosphere system

2 ROOT WATER UPTAKE MODEL

Defining microscopic interaction between soil and root system needs detail of each single root and its interaction with the surrounding soil (Figure 2). Due to the complexity of this system, it is preferred to apply the macroscopic approach the integrated properties of the entire root system. In other words, in macroscopic approach it is assumed that both soil and roots are continuous media. Therefore, the entire root zone is assumed to extract moisture from small differential volumes of the root zone, and the water uptake by roots is represented by a volumetric sink term in the unsaturated flow equation;

$$\frac{\partial \theta}{\partial t} = \nabla.(k\nabla \psi) - \frac{\partial k}{\partial z} - S(x,y,z,t) \qquad \textbf{(1)}$$

where, $\theta\ (= V_W / V)$ is the volumetric moisture content, (V_w = volume of water, V = total volume), ∇ is the divergence vector, ψ is the soil suction, k is the hydraulic conductivity, z is the vertical coordinate (downward is positive) and $S(x,y,z,t)$ is the root water uptake at point (x,y,z) at time t.

A previous study by Indraratna *et al*. (2006) presented a mathematical model for the tree root water uptake distribution within the root zone. The proposed model combines the effects of soil matric suction, root density and potential transpiration, where the rate of tree root water uptake is given by:

$$S(x,y,z,t) = f(\psi).G(\beta).F(T_P) \qquad \textbf{(2)}$$

where, $G(\beta)$ is the root density factor, $f(\psi)$ is the soil suction factor, and $F(T_P)$ is the potential transpiration factor. The most appropriate function for $f(\psi)$ is suggested by Feddes et al. (1978) as follows:

$$\left\{ \begin{array}{ll} f(\psi) = 0 & \psi < \psi_{an} \\ f(\psi) = 1 & \psi_{an} \le \psi < \psi_d \\ f(\psi) = \dfrac{\psi_w - \psi}{\psi_w - \psi_d} & \psi_d \le \psi < \psi_w \\ f(\psi) = 0 & \psi_w \le \psi \end{array} \right\} \qquad \textbf{(3)}$$

where, ψ_w is the soil suction at wilting point, ψ_d and ψ_{an} are the highest and lowest values of ψ at $S = S_{\max}$, respectively, where $S_{\max}$ is the maximum rate of root water uptake. The following two equations have been suggested by Indraratna *et al*. (2006) for the root density factor and the potential transpiration factor, respectively:

$$G(\beta)=\frac{\tanh(k_3\beta_{\max}e^{-k_1|z-z_0|-k_2|r-r_0|})}{\int_{V(t)}\tanh(k_3\beta_{\max}e^{-k_1|z-z_0|-k_2|r-r_0|})dV} \quad \textbf{(4)}$$

$$F(T_P)=\frac{T_P(1+k_4z_{\max}-k_4z)}{\int_{V(t)}G(\beta)(1+k_4z_{\max}-k_4z)dV} \quad \textbf{(5)}$$

In the above equations, k_1 and k_2 are two empirical coefficients depending on the tree root system and type, k_3 is an experimental coefficient, z is vertical coordinate, r is radial coordinate, $\beta_{\max}$ is the maximum root length density which is located at the point $(r,z)=(r_0,z_0)$, T_p is the rate of potential transpiration, k_4 is an experimental coefficient to represent the effect of depth on the potential transpiration distribution, and $V(t)$ is the root zone volume at time t.

3 VERIFICATION OF THE ROOT WATER UPTAKE MODEL

To verify the model developed for root water uptake rate, a case history reported by Biddle (1983) has been considered for a lime tree grown in Boulder clay. The estimated parameters, based on the available literature, are shown in Table 1. Figure 3 illustrates the mesh and element geometry and boundary conditions of the finite element model. Using ABAQUS software, a two-dimensional plane strain mesh employing 4-node bilinear displacement and pore pressure elements (CPE4P) was considered.

Table 1: Parameters applied in the finite element analysis.

Parameter	Value	Reference	Comments
ψ_{an}	4.9 kPa	Feddes *et al.* (1978)	Clayey soil with air content of 0.04
ψ_w	1500 kPa	Feddes *et al.* (1978)	$1500<\psi_w<2000$ kPa
ψ_d	40 kPa	Feddes *et al.* (1978)	$40<\psi_d<80$ kPa
γ	21 kN/m^3	Powrie *et al.* (1992)	Typical value for Boulder clay
$r_{\max}$	9m	Biddle (1983)	Estimated from field measurements $(7m<r_{\max}<11m)$
$z_{\max}$	1.5m	Biddle (1983)	Estimated from field measurements
k_s	10^{-10} m/s	Lehane and Simpson (2000)	Typical value for Boulder clay
PI	23	Biddle (1983)	Measured
e_0	0.60	Powrie *et al.* (1992)	Typical value for Boulder clay
C_c	0.13	Skempton (1944)	Typical value for Boulder clay

The authors' theoretical model representing the rate of root water uptake distribution within the root zone was included in the FE analysis through appropriate Fortran subroutines. The overall mesh consisted of 1326 nodes and 1250 elements. The boundary conditions of the finite element model are illustrated schematically in Figure 3. The flux boundary at the surface is controlled by both climatic conditions and soil properties. In this study, it is assumed that rainfall and evaporation are in balance and thus a "no water in-flow" condition is applied at the surface. According to the field measurements reported by Biddle (1983), the initial pore water pressure can be assumed as hydrostatic with the watertable located 13m below the surface.

This numerical analysis is based on the basic effective stress theory of unsaturated soils incorporated in the ABAQUS finite element code. The effective stress in the unsaturated soil is given by Bishop (1959):

$$\sigma'_{ij}=\sigma_{ij}-u_a\delta_{ij}+\chi(u_a-u_w)\delta_{ij} \quad \textbf{(6)}$$

where, σ'_{ij} is the effective stress of a point on a solid skeleton, σ_{ij} is the total stress in the porous medium at the point, u_a is the pore air pressure, u_w is the pore water pressure, δ_{ij} is Kronecker's delta ($\delta_{ij}=1$ when $i=j$ and $\delta_{ij}=0$ when $i\neq j$), and χ is the effective stress parameter attaining a value of unity for saturated soils and zero for dry soils. Bishop's effective stress concept for predicting shear strength and volume change in unsaturated soils has recently been discussed and validated by Khalili *et al.* (2004).

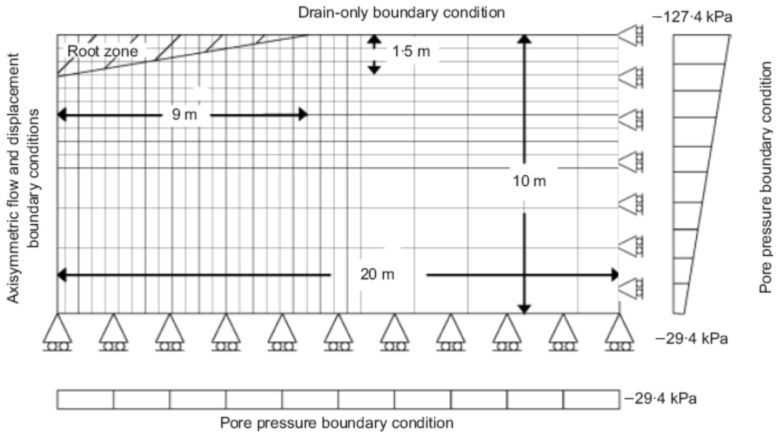

Figure 3: The geometry and boundary conditions of the verification model (after Indraratna *et al*., 2006)

The soil-water characteristic curve employed in this study is shown in Figure 4. A family of curves for different values of $w \times PI$ is shown in Figure 4, where w is the fraction of soil passing sieve #200 (75 μm)as an index between 0 to 1, and PI is the plasticity index (Zapata *et al*., 2000).

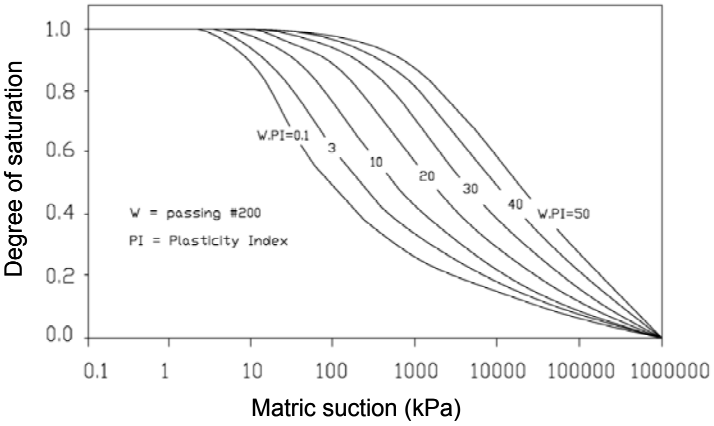

Figure 4: Predicted soil water characteristic curve based on $W \times PI$ (after Zapata *et al*., 2000).

The finite element analysis is conducted in two stages: (i) geostatic and (ii) consolidation. The first stage is to ensure that the analysis commences from a state of equilibrium under geostatic loading. The consolidation stage is to avoid non-physical oscillations and possible divergence problems caused by non-linearities. This stage includes a transient analysis of partially saturated soil under transpiration, starting with 1-day intervals and then continued for 1–year, with continuous root water uptake.

The coefficient of unsaturated soil permeability has been calculated based on Brooks and Corey (1964), thus:

$$k = k_s(e)S_e^{\frac{2+3\lambda}{\lambda}} \tag{7}$$

$$S_e = \left[\frac{S_r - (S_r)_{residual}}{1-(S_r)_{residual}}\right] \tag{8}$$

where, $k_s(e)$ is the saturated coefficient of permeability estimated based on the well known Kozeney-Carman equation, S_e is the effective degree of saturation, S_r is the degree of saturation, $(S_r)_{residual}$ is the residual degree of saturation, and λ $(=\Delta \log S_e / \Delta \log \psi)$ is the slope of the soil water characteristic curve on a log-log plot.

As fluid passes through a porous medium, a coupled flow-deformation analysis of unsaturated soil is required to capture the 3-phase interaction among the soil, air, and water. The governing equations for pore fluid diffusion and deformation are a combination of Equation (1) and the relevant deformation equations. The soil is Boulder clay whose behaviour can be defined by

$$de^{el} = C_c \ln(\frac{p_0 + dp}{dp}) \tag{9}$$

where, de^{el} denotes the change of void ratio in the element, C_c is the compression index, p_0 is the initial mean effective stress, and dp is the mean effective stress change on the soil skeleton. The effect of osmotic suction is assumed to be negligible. The material properties and parameters used in the finite element analysis were given earlier in Table 1, and the additional assumed parameters are given in Table 2.

Table 2: Parameter values assumed in the finite element analysis in the verification model

Parameter	Value	Comments
r_0	6 m	Radial coordinate of the maximum root density point
z_0	0.50 m	Vertical coordinate of the maximum root density point
$\beta_{\max}(t)$	25 m^{-2}	Taken from the general shape or root suggested by Landsberg (1999)
k_3	0.0874 m^{-1}	As above
k_4	0.014	Coefficient of potential transpiration distribution
k_1	10	Coefficient of vertical root distribution
k_2	0.30	Coefficient of horizontal root distribution
ν	0.30	Typical Poisson's ratio for clayey soils
T_P	3 mm/day	Estimated average potential transpiration rate for U.K. (UNEP World Atlas of Desertification)
Passing #200	55%	Typical value for Boulder clay

A comparison between the field measurements and the FEM predictions for moisture content reduction around the lime tree is presented in Figure 5. The numerical model results are in accordance with the field observations reported by Biddle (1983). The main differences noted between field data and the predictions are observed at 6-8 m distance away from the tree trunk. This discrepancy is attributed to the simplicity of the assumed root zone shape. In addition, the foliage prevents uniform distribution of rainfall around the tree. As a result, moisture content can increase at the canopy edges, thereby further contributing to this disparity

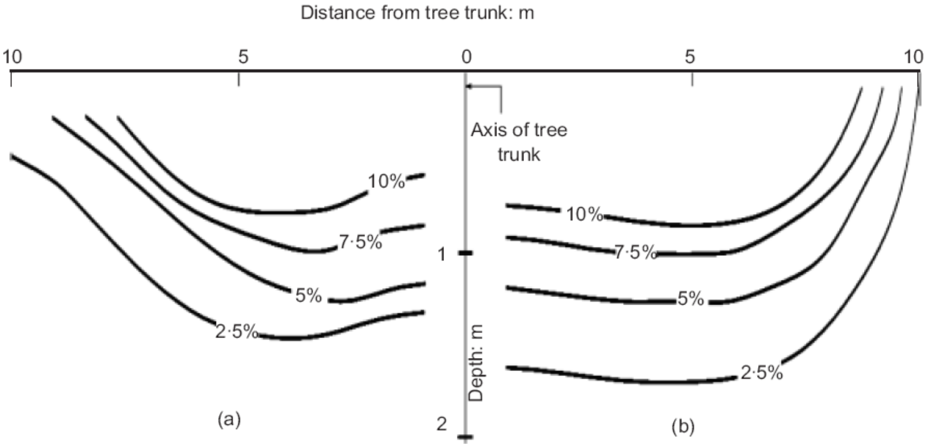

Figure 5: Contours of volumetric soil moisture content reduction (%) close to a lime tree: (a) Biddle (1983), (b) FEM predictions (Indraratna *et al*., 2006)

The maximum change in the soil matric suction from the finite element analysis (Figure 6) is found at about 0.5m depth, which coincides with the same location of the maximum root density. Figure 7 shows the ground settlement at various depths. In this analysis, only the suction related settlement was considered. On the surface, the predicted 80mm settlement beside the tree trunk decreases to less than 20 mm, at a distance 10 m away from the trunk. As shown in Figure 7, the location of the maximum settlement is closer to the trunk at shallower depths, which tends to coincide with the points of maximum change in suction (Figure 6).

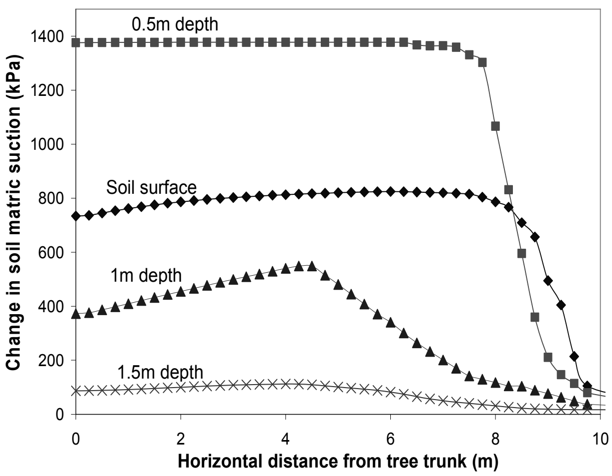

Figure 6: Predicted soil matric suction in different depths.

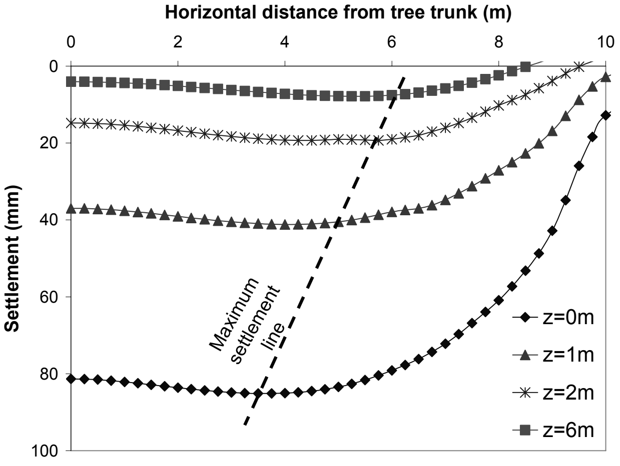

Figure 7: Ground settlement at various depths.

It was shown that the numerical analysis incorporating the proposed model could predict the variation of moisture content surrounding the tree trunk. Knowing the moisture content variation, the development of matric suction can be predicted reasonably well using the soil water characteristic curve. Native biostabilisation improves the shear strength of the soil by increasing the matric suction, and also decreases the soil movements. This contribution from trees grown along rail corridors and rail slope is of immense benefit for improving track stability in problematic soil. In other words, native vegetation generating soil suction is comparable to the role of prefabricated vertical drains with vacuum pressure, in terms of improved drainage (pore water dissipation), and associated increase in shear strength. In addition, the tree roots provide a natural reinforcement effect, which the current model has not simulated thus far.

4 PARAMETRIC STUDY AND SENSITIVITY ANALYSIS

4.1 DESCRIPTION OF REFERENCE PROBLEM AND PARAMETRIC STUDY

A two dimensional finite element analysis is used to conduct a sensitivity analysis of the relevant model variables. The finite element mesh, along with the specific boundary conditions, are shown in Figure 8. Because of symmetry, a zero flux boundary was applied along the left boundary. Root water uptake was modeled as a moisture flux boundary, applied along the top surface of all elements within the root zone. The mesh used in this simulation consists of bilinear strain quadrilateral element (CPE4P) with 4 displacement and four pore pressure nodes positioned at the corners of each element. The entire FE mesh consists of 13,041 nodes and 12,800 elements. In the numerical model, only the matric suction component was considered, and the osmotic suction component was neglected. During the parametric study, the magnitude of one parameter was varied while keeping the other parameters constant at their initial values. The initial values of all parameters considered here are summarised in Table 3. Also, it is assumed that a steady state condition is reached when the rate of change in matric suction $(d\psi / dt)$ is less than or equal to $10^{-6}\, kPa/s$.

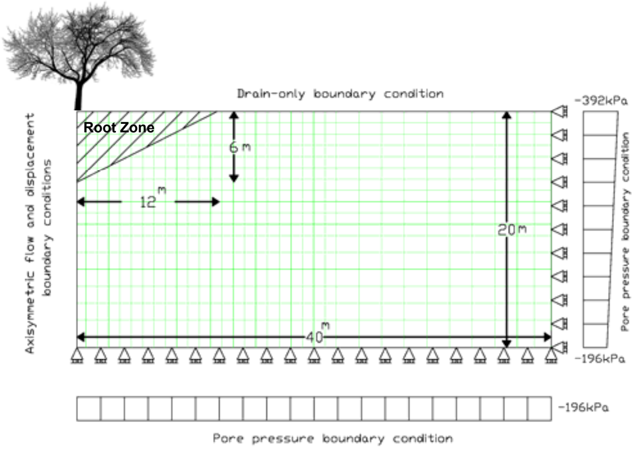

Figure 8: The geometry and boundary conditions of the FE model

Table 3: The initial assumed parameter values in the numerical parametric study.

Parameter	Value	Comments
(r_0, z_0)	(4m, 2m)	Corresponding to radial and vertical coordinate of gravity centre of root zone
$\beta_{\max}(t)$	25 m^{-1}	Taken from the general shape suggested by Landsberg (1999)
$k_1 = k_2$	2 m^{-1}	Applied by Knight (1999)
k_3	8.74×10^{-2} m^{-2}	Taken from the general shape suggested by Landsberg (1999)
k_4	0.014 m^{-1}	Assuming $H_{root} = -76.5m$ and $R_c = 0.05$ *
$(r_{\max}, z_{\max})$	(12m, 6m)	Root zone boundary
ψ_{an}	4.9 kPa	Feddes et al. (1976), Clay soil and air content of 0.04
ψ_d	40 kPa	Feddes et al. (1976; 1978), $40 < \psi_d < 80$ kPa
ψ_w	1500 kPa	Feddes et al. (1976; 1978), $1500 < \psi_w < 2000$ kPa
γ_d	18 kN/m^3	Typical earth soil
C_s	0.05	Average value for clay soils in vicinity of building foundations
k_s	5×10^{-8} m/s	Typical value for clay soils in vicinity of building foundations (e=1)
passing #200 × Plasticity Index	20	-
T_P	8 mm/day	Myers and Talsma (1992), Pinus Radiata tree (ACT, Australia)
Initial void ratio (e_0)	1	Typical clay soil

*by comparing Equations (5) and Nimah and Hanks (1973) model, k_4 can be estimated by k_4=-(1+R_c)/H_{root}, where H_{root} is the effective water potential in the root at the soil surface where z is considered zero and R_c is the flow coefficient in the plant root system.

Considering the initial parameters, the predicted profile of the steady state soil matric suction is presented in Figure 9. The matric suction varies from a maximum value of 1081 kPa at point (r_0, z_0) to 196 kPa at 20 m depth. As expected, the maximum matric suction change is at the centre of gravity of the root mass (r_0, z_0) and it decreases with distance away from this point. The deformation of the soil profile due to the root water uptake is predicted through a coupled flow-deformation analysis, considering the stress-deformation equations. The ground settlement at various depths under steady state conditions is shown in Figure 10.

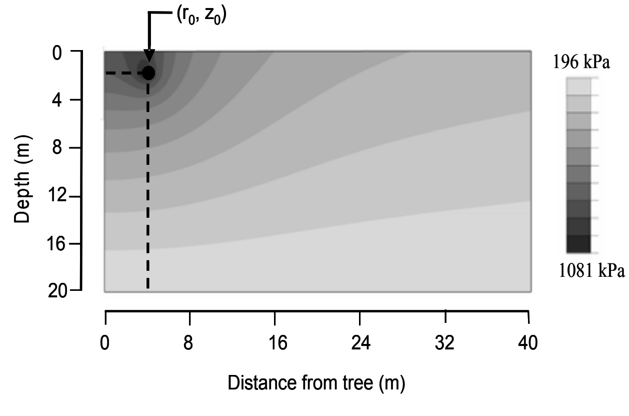

Figure 9: Matric suction profile in steady state condition

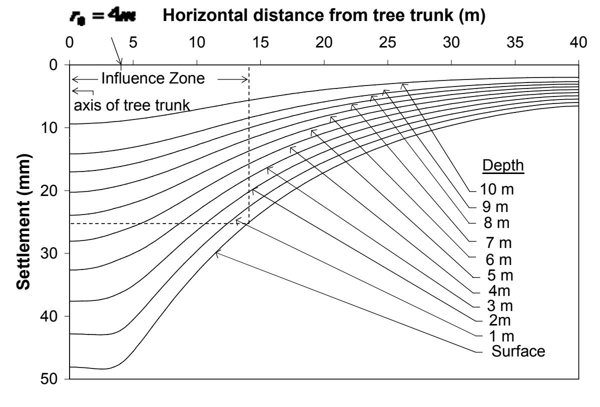

Figure 10: Ground settlement profile at various depths.

The radius of the influence zone for which the surface settlement is at least 25 mm (i.e. change of curvature of the settlement plots) is shown to be about 14 m. The ground settlement decreases rapidly with the horizontal distance from the tree trunk, and beyond 30 m, the predicted settlement is not significant.

4.2 EFFECT OF WILTING POINT VALUE (ψ_w)

It seems that the value of the soil suction at wilting point (ψ_w), based on Feddes *et al.*'s (1978) formula, strongly influences the value of the $f(\psi)$. To confirm this point, six analyses are performed similar to the reference case, except for the value of suction at wilting point, which changes from 1500kPa to 3000kPa (see Figures 11 and 12).

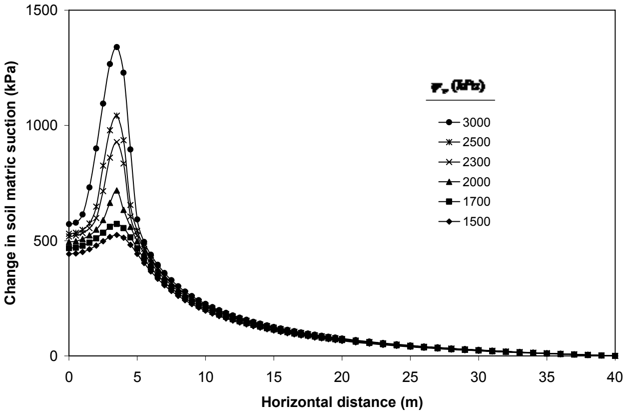

Figure 11: Effect of ψ_w on matric suction change at soil surface.

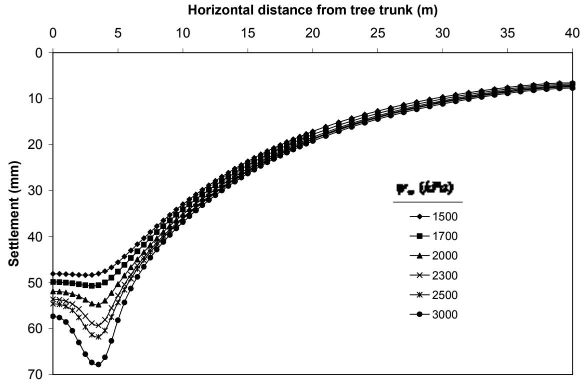

Figure 12: Effect of ψ_w on soil surface settlement.

When ψ_w increases, the value of $f(\psi)$ (in the range of $\psi_d \le \psi \le \psi_w$) increases and consequently the rate of root water uptake increases. As Figures 11 and 12 present, soil matric suction change and soil settlement increase by ψ_w. It can be noted that the maximum suction changes occur at point (r_0, z_0).

4.3 EFFECT OF VERTICAL ROOT DENSITY DISTRIBUTION FACTOR (k_1)

To evaluate the influence of vertical root density distribution factor (k_1), the results of four analyses with k_1 values equal to 0.1, 0.5, 1, and 5 are compared to each other. As Figures 13 and 14 show, the maximum soil suction change increases with k_1 value. Meanwhile, by decreasing the vertical root density distribution factor, the point of the maximum soil suction change moves toward tree trunk. On the other hand, the soil suction change at points away from the maximum point ($|r - r_0| > 1\,m$) decreases with the value of k_1. Thus, as Figure 14 clearly shows, the soil suction change under the tree trunk decreases with the value of k_1.

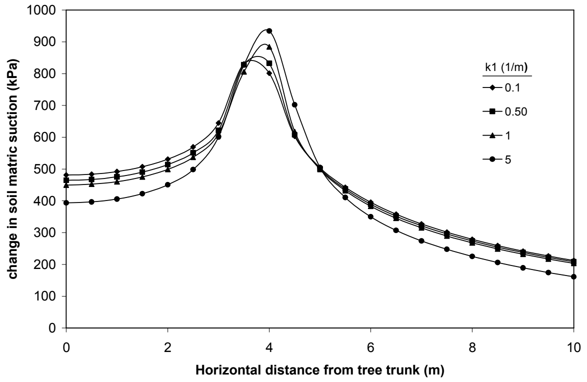

Figure 13: Effect of k_1 on soil matric suction change at 2 m depth.

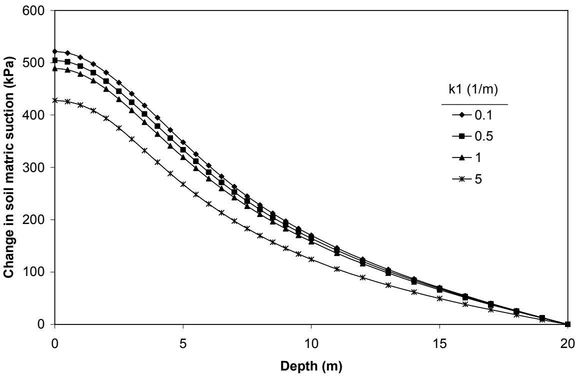

Figure 14: Effect of k_1 on soil matric suction change under the tree trunk.

4.4 EFFECT OF HORIZONTAL ROOT DENSITY DISTRIBUTION FACTOR (k_2)

The analyses to examine the effect of horizontal root density distribution factor are similar to the reference case except for the value of k_2 that changes from 0.1 to 5. Figure15 illustrates that the maximum soil matric suction change increases with the value of k_2, and the point of the maximum suction change moves towards the tree trunk and the soil surface. On the other hand, as Figure 16 shows soil suction on the surface decreases with k_2 value.

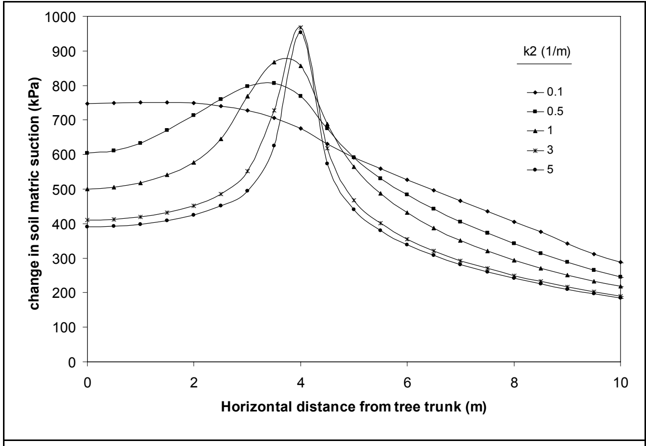

Figure 15: Effect of k_2 on soil matric suction change at 2 m depth.

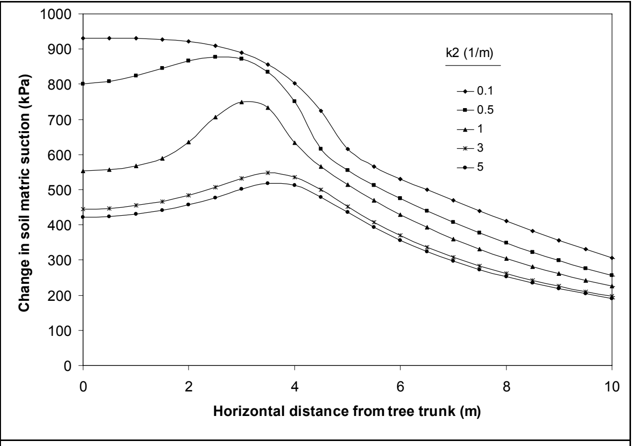

Figure 16: Effect of k_2 on soil matric suction change on soil surface.

4.5 SENSITIVITY ANALYSIS OF THE GROUND SETTLEMENT

The maximum allowable settlement is an essential criterion in foundation design. Accordingly, prediction of ground settlement induced by tree transpiration can enhance the design approach of foundations in the vicinity of tree roots. In this section, sensitivity of the maximum settlement with respect to a number of parameters is investigated employing sensitivity index defined by,

$$(I_S)_i = \frac{\dfrac{\partial D_{\max}}{\partial u_i}}{\dfrac{D_{\max}}{u_i}} \qquad \textbf{(10)}$$

where, $(I_S)_i$ is the sensitivity index of i th parameter, $D_{\max}$ is the maximum vertical deformation, and u_i is the parameter which influences the ground settlement. Based on the sensitivity index, parameters can be categorised as follows:

$$\begin{cases} 0\% < I_S < 20\% & \textit{Insensitive} \\ 20\% \le I_S < 50\% & \textit{Sensitive} \\ 50 \le I_S & \textit{Very sensitive} \end{cases} \qquad \textbf{(11)}$$

Figure 17 shows the results of the sensitivity indices of various parameters.

The sensitivity analysis results demonstrated in Figure 17 are based on the assumed initial parameters and the applied range of parameters. Table 4 summaries the sensitivity of the maximum ground settlement with respect to variation of the model parameters.

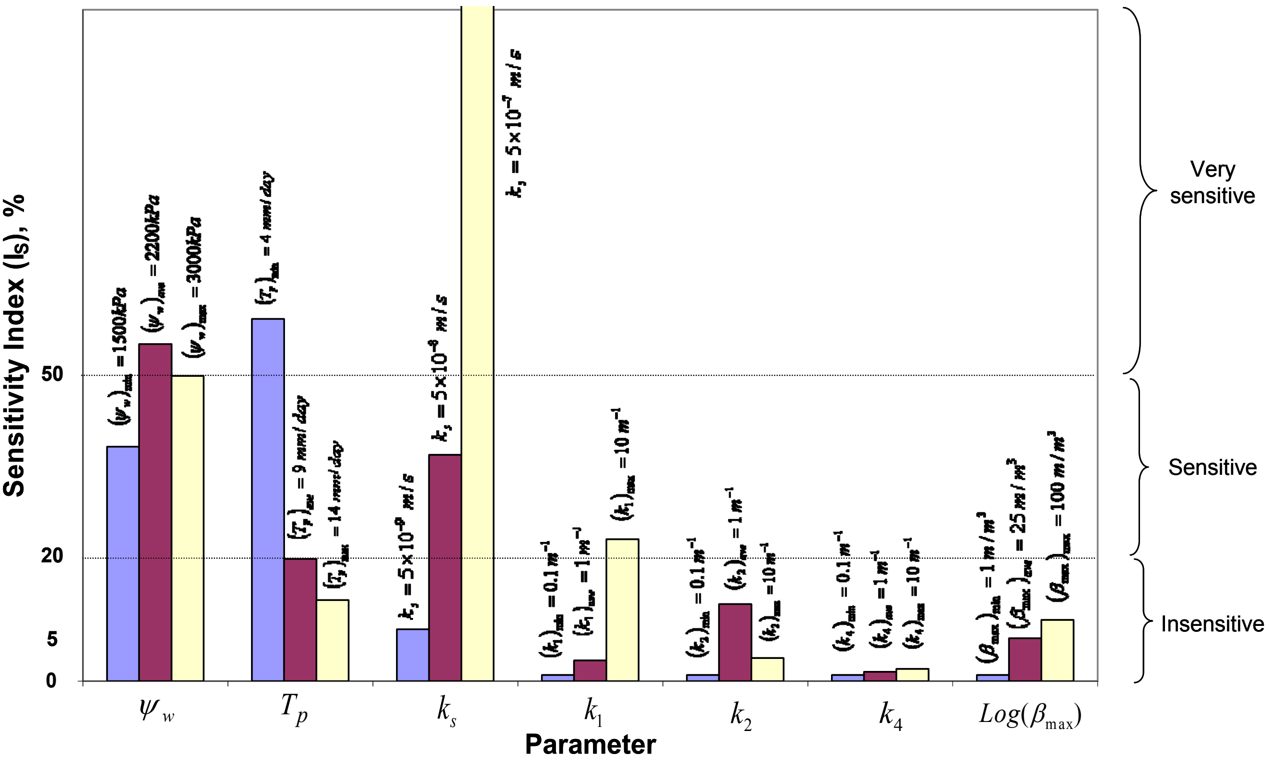

Figure 17: Results of the sensitivity analysis for the maximum ground settlement.

Table 4: Sensitivity of the maximum settlement to some of the parameters

	Insensitive	Sensitive	Very Sensitive
$\psi_w\ (kPa)$	-	1500 - 1900	1900 - 3000
$T_p\ (mm/day)$	9 - 14	5 - 9	4 - 5
$k_s\ (m/s)$	$5\times10^{-9} - 3\times10^{-8}$	$3\times10^{-8} - 7\times10^{-8}$	$7\times10^{-8} - 5\times10^{-6}$
$k_1\ (m^{-1})$	0.1 - 6	6 - 10	-
$k_2\ (m^{-1})$	0.1 - 10	-	-
$k_4\ (m^{-1})$	0.01 - 10	-	-
$Log(\beta_{max})$	0 - 2	-	-

The most sensitive parameters are: the wilting point suction, saturation permeability when the coefficient is relatively high ($>3\times10^{-8}\ m/s$), the rate of potential transpiration at lower values (i.e. $T_p < 9\ mm/day$), and vertical root distribution coefficient (k_1) when the coefficient is high ($>6\ m^{-1}$). Parametric studies have also been conducted for T_p and k_s, but not shown in this paper. As expected, a higher rate of transpiration creates a higher matric suction change, whereby the highest rate of matric suction change is at the point of maximum root density. Furthermore, soil permeability influences the soil moisture movement, thereby affecting the soil matric suction distribution. The analysis results show that the soil settlement decreases with the increasing value of permeability. When the permeability is smaller, the generated matric suction within the soil matrix is higher and, consequently, the effective stresses increase causing larger settlements.

5 CONCLUSIONS

In order to investigate the effects of tree transpiration on ground condition, a numerical model using the finite element analysis has been developed considering the coupled flow-deformation equations. The finite element mesh is formulated using partially or fully saturated soil elements, which are capable of capturing the role of unsaturated permeability and the degree of saturation at various levels of matric suction. Tree root suction was considered through the model developed by Indraratna *et al.* (2006) which takes into account soil matric suction and distribution of root density and potential transpiration.

Existing data from previously published literature have been used to validate the analysis. It has been found that given the approximation of the assumed root geometry and model parameters, the agreement between predictions and field data is promising. The proposed root water uptake and transpiration model verifies that the suction induced by the tree roots contributes to a substantial gain in shear strength. Similar to prefabricated vertical drains, the tree roots induce good drainage, pore water pressure dissipation and in addition provide natural reinforcement of the soil. As the influence zone of each tree can be several meters in radius, the methodological planting of native trees along rail corridors at a practical distance away from the track is currently considered by rail organizations in Australia. Considering various soil conditions, the type of vegetation and atmospheric conditions, the proposed mathematical model for biostabilsation is most useful to predict the formation behaviour in a rail track environment.

An in-depth analysis of the effects of several important variables has shown that a complex interaction exists between tree and soil properties. The findings of this study confirm that a number of parameters are required to be measured or estimated accurately for a proper foundation design. The soil permeability, the wilting point suction, the root length density and the rate of potential transpiration significantly influence the ground behaviour. Other parameters including soil properties (e.g. consolidation parameters, strength parameters and soil water characteristic curve) should be measured accurately in laboratory or field as they are also important factors in the analysis.

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