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CASE STUDY ON THE INFLUENCE OF TRANSPIRATION ON THE GROUND BEHAVIOUR

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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. A mathematical model for the rate of root water uptake has been developed 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 model. A two dimensional finite element approach has been employed to solve the transient coupled flow and deformation equations. In order 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.

INTRODUCTION

Soil conditions on construction sites have continued to deteriorate throughout the world due to over population in metropolitan areas. These conditions have compelled engineers to construct earth structures, major highways, and railways over expansive clays, and compressive clay deposits. Today, Australia's rail network incorporates one of the world's largest and most complex metropolitan and interstate networks covering all states and territories, totaling some 44,000 kilometres. Following heavy rains, water seeps underneath the tracks often causing uneven settlement and potentially hazardous problems if not addressed in a timely manner. Bioengineering aspects of native vegetation are currently being used to improve the soil stiffness, stabilise slopes and control soil erosion.

Tree roots provide three independent stabilising functions: (a) reinforcement of the soil, (b) dissipation of excess pore pressure and (c) establishing a matric suction that will increase the shear strength. The matric suction established in the root zone propagates radially and contributes to stabilise the tracks near the root zone. Most attempts to quantify the effects of vegetation have focused on the mechanical strengthening provided by the roots, but have ignored the implications of transpiration on the pore water pressure. When modelling a vegetated vadose zone, a detailed description of the root water uptake is required. Existing methods only consider a simplified model that is implemented mainly in the flow equation. Although current design standards such as the Uniform Building Code (1997) and Standard Australia, AS2870 (1996) provide guidelines for the design and construction of footings and structures on expansive clays, none of them provide any guidelines on how ground desiccation caused by native vegetation should be included. Given the importance of the vadose zone in most geo-environmental projects, there is a strong need to develop a better understanding of how trees, including root based suction, influence behaviour within this zone.

The main objective of this study is to validate the model developed by the authors for estimating the root water uptake. Then an integrated transient model considering soil water extraction by roots within vadose zone to simulate the ground movement under the influence of vegetation has been developed. Developing an analytical solution to predict water flow in soil-vegetation porous media would be very complicated. Hence, numerical modelling becomes the choice to analyse and predict the movement of water in this study. The results have then been compared with field measurements conducted at Miram site in Victoria, Australia to verify the numerical predictions.

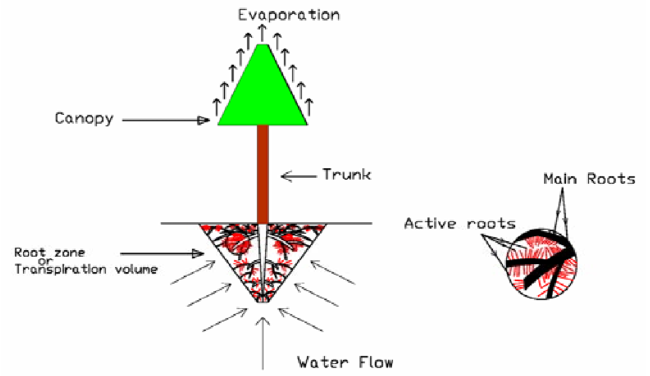
CONCEPTUAL MODEL FOR TRANSPIRATION DISTRIBUTION

The loss of moisture from the soil may be categorised as (a) water used for metabolism in plant tissues, and (b) water transpired to the atmosphere. However, as suggested by

Radcliffe et al. (1980), the volume of water required for photosynthesis or metabolism in plant tissues compared to the total water uptake by roots is negligible. Total transpiration can then be assumed to be the same as water uptake through the root zone. Therefore, the key variable for estimating the transpiration rate is the rate of root water uptake, which depends on the geological, hydrological, and meteorological conditions. Figure 1 shows a schematic illustration of the soil-plant-atmosphere interaction. The rate of transpiration depends on the rate of root water uptake, hence:

$$T(t) = \int_{V(t)} S(x, y, z, t)\, dV \tag{1}$$

where, $T(t)$ is the transpiration rate at time t, $S(x, y, z, t)$ is the root water uptake at point (x, y, z) at time t and if $V(t)$ is the volume of root zone at time t, dV denotes a small volumetric change.



(a) (b)

Figure 1. Schematic sketch of soil-plant-atmosphere system, (a) soil-plant-atmosphere interaction and (b) active and main roots.

As mentioned above, the three independent features that are considered in detail in the root water uptake model are soil suction, root distribution and potential transpiration. It is assumed that the function of the root water uptake rate can be expressed as a product of three separate functions. Consequently, the rate of tree root water uptake is given by:

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

where, $\beta(t)$ is root length density at time t, $G(\beta(t))$ is the root density factor, $T_p(t)$ is the rate of potential transpiration at time t, $F(T_P(t))$ is the potential transpiration factor and $f(\psi(t))$ is the soil suction factor.

Potential transpiration is defined as the evaporation of water from plant tissues to the atmosphere, when the soil moisture content is unrestricted. Therefore the maximum possible root water uptake is called the potential transpiration that relates to meteorological characteristics, as well as the condition and age of the plant. Although a small amount of water vapour may be lost through minute openings (called Lenticles) in the bark of young twigs and branches, by far the largest proportion (more than 90%) escapes from leaves. Indeed, the process of transpiration is strongly tied to the leaf anatomy.

In this study, it is assumed that the potential transpiration rate from a whole plant is proportional to the leaf area. Therefore, the potential transpiration rate (mm/day) from a whole plant can be calculated by:

$$T_p(t) = \frac{LAI(t) T_r(t)}{\rho_w} \tag{3}$$

where, $T_p(t)$ is the potential transpiration rate at time t per area of ground covered by the plant ($m^3 s^{-1} m^{-2}$), $LAI(t)$ is the leaf area index (m^2/m^2), which is leaf surface area per unit of the land surface area, $T_r(t)$ is the potential transpiration rate per unit leaf area ($kg\ s^{-1}\ m^{-2}$), and ρ_w is the water density ($kg\ m^{-3}$).

According to Wu et al. (1999), the leaf area index can be calculated by:

$$LAI(t) = LAI_{\max} \frac{e^{-d_g (t/t_f - c_g)^2} - e^{-d_g c_g^2}}{1 - e^{-d_g c_g^2}} \tag{4}$$

where, $LAI_{\max}$ is the maximum leaf area index, c_g is the normalised peak time when leaf area index is at its maximum value, d_g a dimensionless coefficient dependent on growth and senescence rate of leaves.

Assuming that the average potential transpiration rate is defined on the average potential transpiration rate per unit leaf area for a well developed tree, this gives:

$$\overline{T}_p = \frac{LAI_{\max} . \overline{T}_r}{\rho_w} \tag{5}$$

where, $\overline{T}_p$ is the average potential transpiration rate per unit area of ground (ms^{-1}), $\overline{T}_r$ is the average potential transpiration rate per unit leaf area, and then substituting Equations (4) and (5) in Equation (3) results in:

$$T_p(t) = \overline{T}_p \frac{e^{-d_g (t/t_f - c_g)^2} - e^{-d_g c_g^2}}{1 - e^{-d_g c_g^2}} \tag{6}$$

In this study, it is assumed that potential transpiration is not distributed uniformly within the root zone because of the root resistance term and a linear distribution with depth for potential transpiration is a more appropriate distribution. Accordingly, Equation (7), which considers the linear distribution of transpiration with depth, is suggested to take into account the effect of potential transpiration,

$$F(T_P) = \frac{T_P(t)(1 + k_4 z_{\max} - k_4 z)}{\int_{V(t)} G(\beta)(1 + k_4 z_{\max} - k_4 z)\, dV} \tag{7}$$

where, $T_p(t)$ is the rate of potential transpiration, and k_4 is an experimental coefficient to involve depth on the potential transpiration distribution, $G(\beta)$ is the root density factor capturing the effect of root density on the root water uptake. According to Fatahi (2007), $G(\beta)$ can be calculated using Equation (8),

$$G(\beta)=\frac{\tanh(k_3\beta_{\max}e^{-k_1|z-z_0|-k_2|r-r_0|})}{\int_{V(t)}\tanh(k_3\beta_{\max}e^{-k_1|z-z_0|-k_2|r-r_0|})dV} \qquad (8)$$

where, k_1 and k_2 are two empirical coefficients depending on the tree root system and type, k_3 is an experimental coefficient representing the influence of root density, z is the vertical coordinate (downward is positive), r is the radial coordinate, $\beta_{\max}$ is the maximum density of root length located at the point $(r,z)=(r_0,z_0)$,.

As discussed by Fatahi (2007), an appropriate representation for $f(\psi)$ based on Feddes et al. (1978) may be considered as follows,

$$\left\{\begin{array}{ll} f(\psi)=0 & \psi<\psi_{an} \\ f(\psi)=1 & \psi_{an}\le\psi<\psi_d \\ f(\psi)=\dfrac{\psi_w-\psi}{\psi_w-\psi_d} & \psi_d\le\psi<\psi_w \\ f(\psi)=0 & \psi_w\le\psi \end{array}\right\} \qquad (9)$$

where, ψ_w is the soil suction at wilting point, the limit at which a particular vegetation is unable to draw moisture from the soil; ψ_d and ψ_{an} (soil suction at anaerobiosis point) are the highest and the lowest values of ψ at $S=S_{\max}$, respectively, while $S_{\max}$ denotes the maximum rate of root water uptake.

Figure 2 shows a typical example of the distribution of initial rate of root water uptake for a Poplar tree. As Figure 2 shows, the maximum rate of root water uptake (RWU$_{\max}$) occurs 3 m away from the tree trunk. For an assumed profile of initial soil suction, the point of RWU$_{\max}$ is located at the point of the maximum root length density.

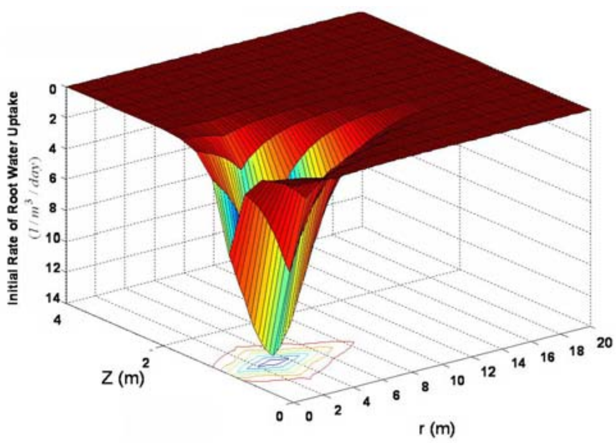


Figure 2. Initial distribution of root water uptake rate.

FIELD AND LABORATORY EXPERIMENTS SUPPLEMENTED WITH NUMERICAL ANALYSIS

This case history is related to the results of a geotechnical investigation conducted near an 11 m high Eucalyptus largiflorens tree. Eucalyptus largiflorens (Black Box) is an Australian native tree, which is very common in the states of New South Wales, Queensland, South Australia, and Victoria. According to Huxley (1992) and Genders (1994), Eucalyptus largiflorens is an evergreen tree, approximately 10-20 m high and 7.5-15 m in spread with rough bark on trunk and branches. It is a slow growing tree with relatively shallow roots that tolerates poor and dry soils, cannot grow in the shade, much preferring sandy, loamy, and clayey soils. The proposed site is at Miram village, which is 15km away from Kaniva, a city in the state of Victoria, Australia. This study examines the model results, field measurements and observations, and also presents laboratory data in comparison with the model predictions.

The climate in Miram is semi-arid with mild winters and long hot summers. The mean daily maximum temperature ranges from 13.7°C in July to 29.7°C in January. The mean monthly rainfall ranges from 20.9 mm in January to 47.7 mm in August, with a mean annual rainfall of 415.3 mm. The mean monthly potential evaporation ranges from 30.45 mm in July to 257.9 mm in January (Bureau of Meteorology, 2006). On an annual basis, the potential evaporation (1483.7 mm/yr) is more than 3 times the average annual rainfall (415.3 mm/yr). Figures 3 and 4 show consecutive graphs for the meteorological conditions used for the Miram area from 2003 until 2006.

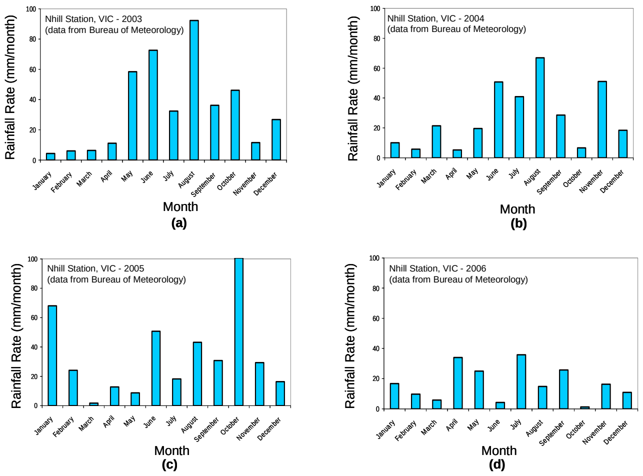


Figure 3. Monthly rainfall data from 2003 until 2006 at Miram area in Victoria

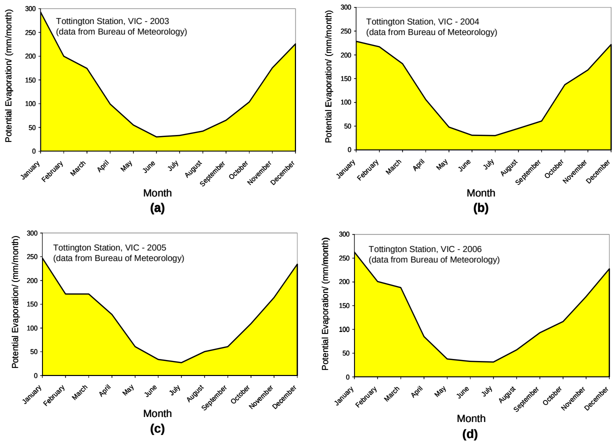


Figure 4. Monthly evaporation rate from 2003 until 2006 at Miram area in Victoria

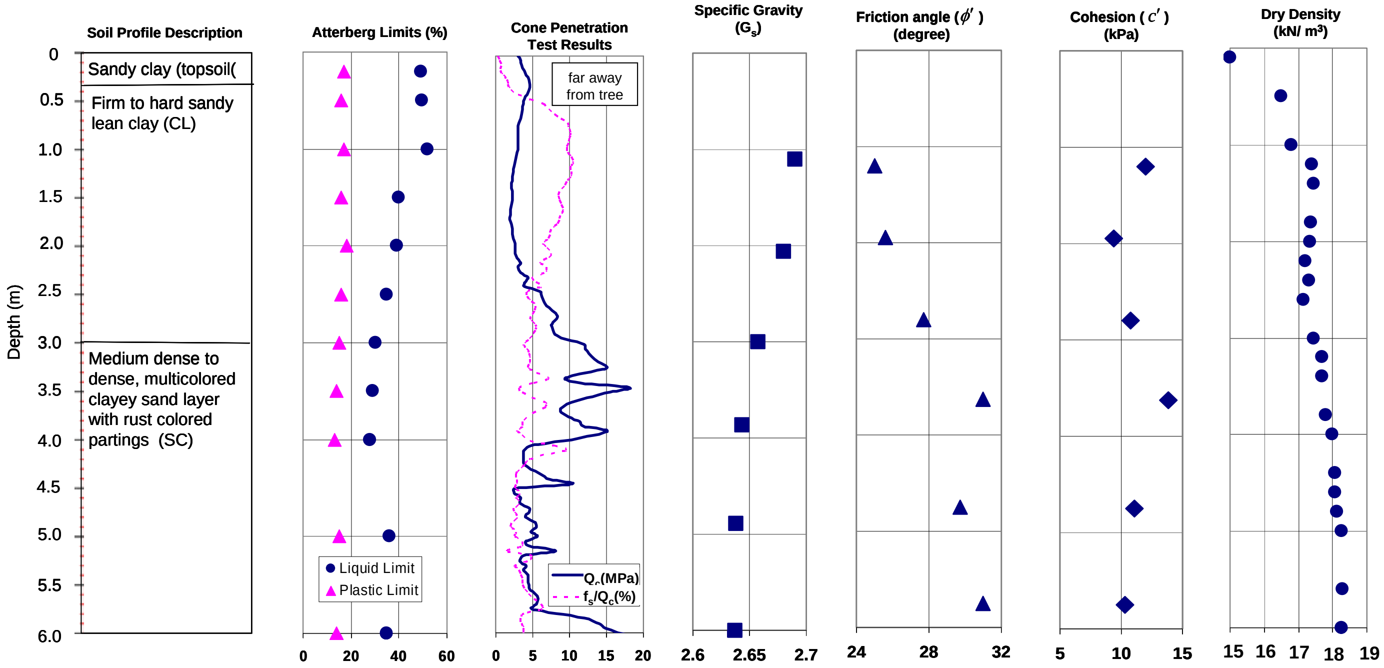


Figure 5. General soil profile and properties at Miram site, VIC, Australia.

Figure 5 shows the average soil profile used at the site for this case study and also the profiles of the Atterberg limits, and the results of the cone penetration test. In addition, the variation of soil permeability with depth is presented in Figure 6.

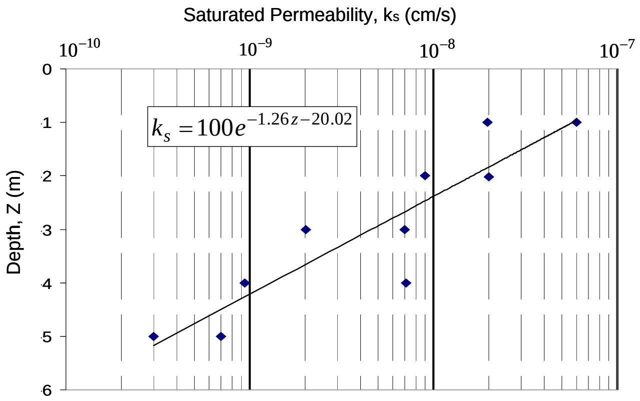


Figure 6. Soil permeability variation with depth at Miram site, VIC, Australia.

The parameters used in this analysis, relating to the interaction between the tree, ground, and the atmosphere, are given in Table 1.

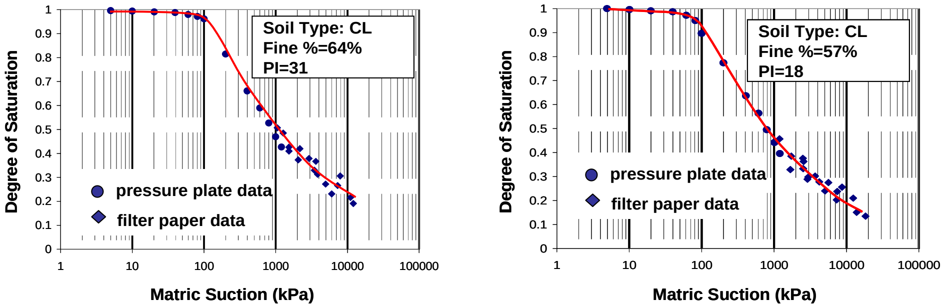
This numerical analysis is based on the effective stress theory of unsaturated soils incorporated in the ABAQUS finite element code. The effective stress in the unsaturated soil is given by Bishop (1959):

$$\sigma'_{ij} = \sigma_{ij} - u_a\delta_{ij} + \chi(u_a - u_w)\delta_{ij} \qquad (10)$$

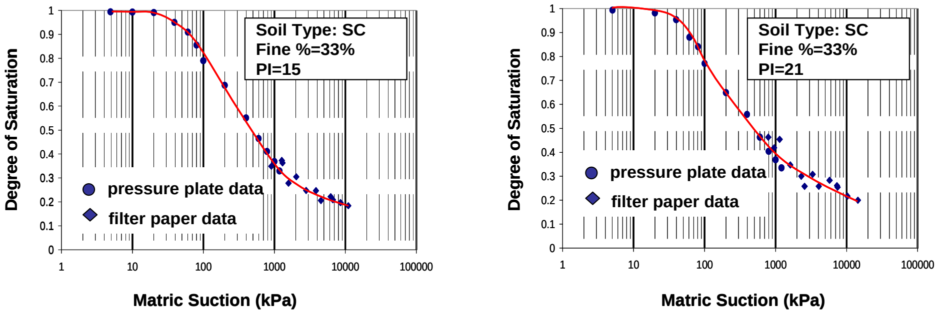
where, σ'_{ij} is the effective stress of a point on a solid skeleton, σ_{ij} is the total stress in the porous medium at the point, u_a is the pore air pressure, u_w is the pore water pressure, δ_{ij} is Kronecker's delta, and χ is the effective stress parameter attaining a value of unity for soils that their matric suction is greater than the air entry value and zero for dry soils. In unsaturated soil mechanics, the term $(u_a - u_w)$ is usually called the matric suction.

Table 1. Parameters of interaction between Black Box tree and ground at Miram

Parameter	Measured Value	Comments
$r_{\max}$	20 m	Estimated from field observation of root zone dimensions
$z_{\max}$	3 m	Estimated from field observation of root zone dimensions
r_0	8.5 m	Radial coordinate of the maximum root density point
z_0	1.2 m	Vertical coordinate of the maximum root density point
$\beta_{f.}$	659000 m^{-2}	Measured according to organic content
k_1	0.35	Measured according to organic content
k_2	0.55	Measured according to organic content
ψ_w	1700 kPa	Estimated from field measurements
ψ_{an}	4.9 kPa	Clayey soil with air content of 0.04 (Feddes et al. 1978)
T_p	80 l/day	Estimated from Jolly and Walker (1996)



(a) **Depth 0-1.5m** (b) **Depth 1.5-3.0m**



(c) **Depth 3-4.5m** (d) **Depth 4.5-6.0m**

Figure 7. Soil water characteristic curves for soil depths of (a) 0-1.5 m, (b) 1.5-3.0 m, (c) 3.0-4.5 m and (d) 4.5-6.0 m.

The material behaviour of the soil (mostly medium to highly over-consolidated clayey soils) has been modelled with an elasto-plastic cap model as presented by Reul and Randolph (2003). In this situation, the analysis is governed by soil stiffness rather than the soil strength, where the deformations occur well below the peak shear stress. In this study, the top 6 m of soil strata has been divided into 4 layers 1.5 m deep. The boundary between the upper clayey soil and lower sandy soil is at a depth of 3 m. Below 6 m, it has been assumed that the properties do not change and are identical to those at 4.5-6.0 m deep. The soil water characteristic curves used in this study are those shown in Figure 7. The material properties and parameters used in the finite element analysis were given earlier in Table 1, and the additional measured parameters are given in Table 2. Figure 8 shows the flow chart to solve the coupled flow-deformation governing equations used in this study considering the developed root water uptake model. In this study, the porous media is modelled by attaching the finite element mesh to the solid phase and then fluid can flow through this mesh.

Figure 9 shows a comparison between the field measurements and the prediction of the numerical model for volumetric moisture content

The numerical results incorporating the developed root water uptake model are in acceptable agreement with the field measurements. Referring to Figure 9, field measurements of moisture content reduction are noticeably different from the finite element predictions close to the tree trunk. This is not surprising as the foliage and the tree trunk alter the uniform distribution of rainfall, and also due to the shadow under the tree canopy, evaporation rate changes as a result of temperature and humidity variations. Consequently, these effects have probably contributed to the disparity between the field data and the finite element predictions.

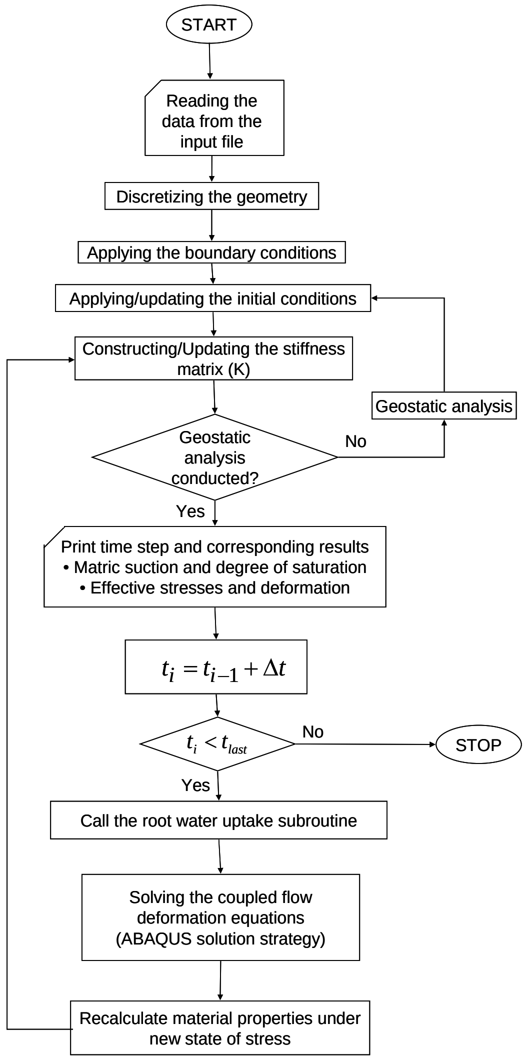


Figure 8. Flowchart of approximate solution of coupled-flow deformation governing equation.

Table 2. Parameter values used in the finite element analysis

Parameter	**Layer I**	**Layer II**	**Layer III**	**Layer IV**	**Description**
γ_d (kN/m^3)	16.6	17.3	17.8	18.2	Dry density
e_0	0.61	0.52	0.47	0.42	In situ void ratio
E (MPa)	25	40	56	87	Initial deformation modulus
ν	0.30	0.33	0.32	0.35	Poisson's ratio
p'_c (kPa)	400	550	700	950	Preconsolidation pressure
β' (deg)	44.53	46.35	51.20	50.70	Slope of the conus yield surface in the $p-t$ plane
d (kPa)	25.32	21.03	27.94	22.19	Intersection of the conus yield surface with t axis
K	0.753	0.741	0.707	0.711	Shape parameters of the conus
α	0.01	0.01	0.01	0.01	Shape parameter of the transition yield surface
R	0.1	0.1	0.1	0.1	Shape parameter of the cap
ψ_d (kPa)	100	80	20	30	Maximum ψ when $S = S_{\max}$
ψ_{air} (kPa)	100	80	20	30	Air entry value

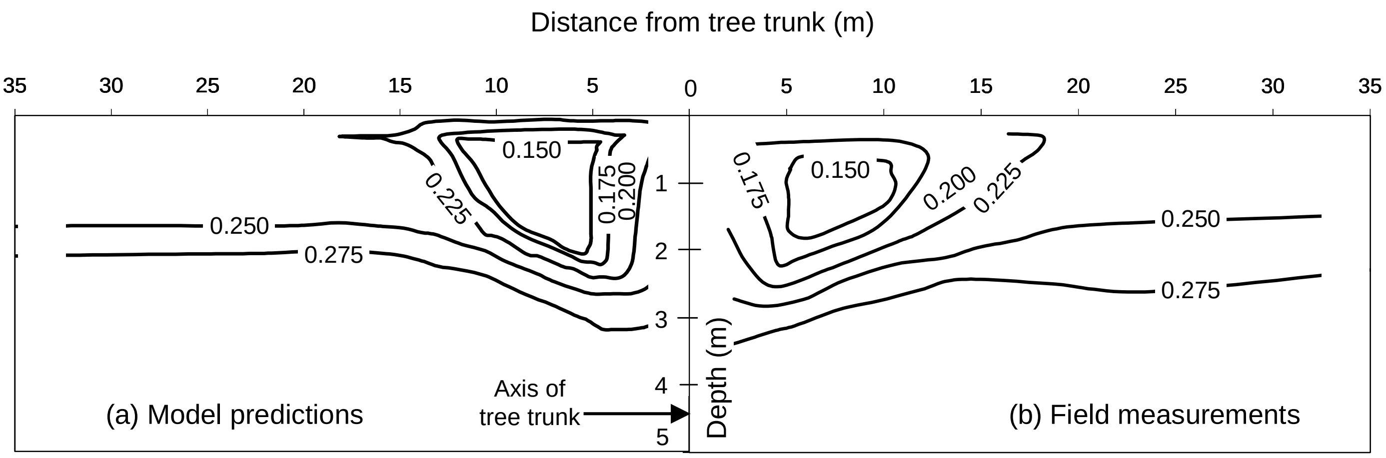


Figure 9. Contours of volumetric soil moisture content reduction in vicinity of the tree (a) current numerical analysis results, (b) field measurements in May 2005.

Figure 10 shows the comparison between the field measurements and model predictions of the soil matric suction in the top 6 m of the soil layer at different lateral distances from the tree trunk.

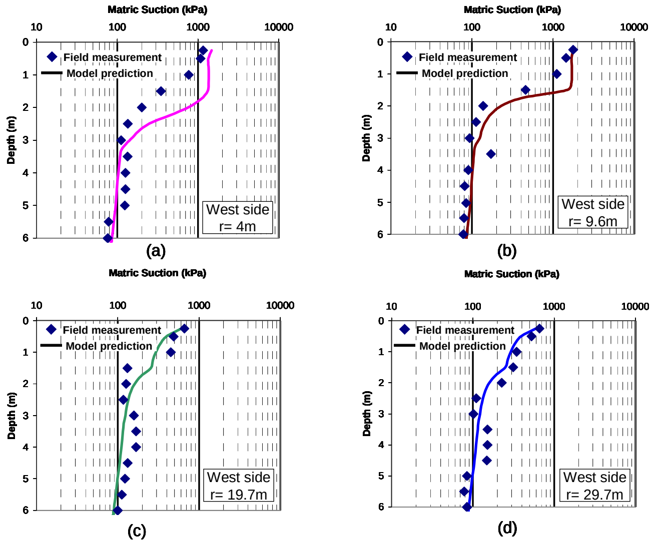


Figure 10. Soil matric suction profiles at (a) 4 m (b) 9.6 m (c) 19.7 m (d) 29.7 m away from the tree trunk at the western side of the tree trunk in May 2005.

It is important to note that part of the difference between field measurements and numerical predictions is related to the individual effect of roots. In the other words, in the numerical analysis, root water uptake as a sink term was considered in the flow equation, but the effect of each root was not considered individually. As the main roots penetrate the soil, there may be a gap between them, which can lead to water collecting in the gap. Since the woody roots are in a denser pattern under the tree trunk and in close proximity, a disparity between the field measurements and predictions in this area seems more likely. Furthermore, the actual field data are expected to be affected by the soil heterogeneity.

Figure 11 shows the model predictions of the profile of ground settlement distribution as a result of evapotranspiration and precipitation in the middle of May 2005.

According to Figure 11, the maximum ground settlement of 200 mm occurs approximately 6 m away from the tree. As expected, the ground settlement that is induced by the soil consolidation, decreased with depth. The ground settlement is caused by both the root water uptake and the evaporation from the soil surface. As Figure 11 shows, the soil surface settlement caused by evaporation is approximately 110 mm. Hence, the rest of the settlement is assumed to be induced by transpiration.

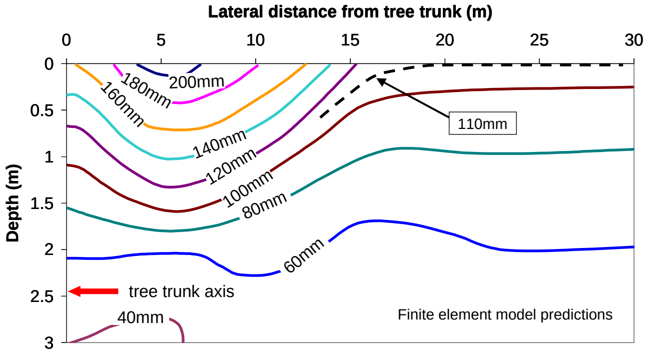


Figure 11. Model predictions for the contours of vertical displacement.

CONCLUSIONS

The model proposed for predicting the rate of root water uptake was included in a numerical analysis using the ABAQUS finite element code to examine the distribution of soil suction and the profile of the moisture content near a single Black Box tree. The results of a numerical prediction of the matric suction and the moisture content around a single Black Box tree located in western Victoria in Australia were compared with the field data taken in May 2005.

There were some uncertainties in some field and laboratory measurements of the soil parameters, the actual distribution of tree roots and atmospheric parameters. Nevertheless, a good agreement was generally obtained between the measured and simulated distribution of soil moisture. A comparison of the results indicated similar trends. It was also shown that a numerical analysis that includes the proposed root water uptake model can reasonably predict the region of maximum matric suction away from the axis of the trunk, as measured in the field. Ground contours for this case study indicated that the maximum settlement after about 3 years occurred away from the trunk on the surface . The proposed model and associated numerical analysis is a promising tool for predicting matric suction induced by transpiration within a soil matrix .

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