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A theoretical model for total suction effects by tree roots

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Abstract

Strengthening soft and weak soil by way of root reinforcement is a well-known strategy that is adopted worldwide. In Australia, native gum trees remain evergreen throughout the year and have been utilised to stabilise transportation corridors by way of reinforcement provided by the roots and the suction generated within the root domain as a function of evapotranspiration through the canopy. A mature gum tree can induce a massive total suction pressure exceeding 30MPa through its root water and solute uptake in terms of matric plus osmotic suction. This cumulative effect of matric and osmotic suctions contributes to the overall shear strength of the soil, but the significant osmotic suction is often ignored in classical geotechnical engineering that does not consider the presence of trees. This study is an attempt to demonstrate the important role of osmotic suction, because it is directly proportional to the solute concentration in the soil and the solute uptake mechanisms of the surrounding vegetated ground.

Keywords

theoretical, roots, effects, tree, model, suction, total

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A theoretical model for total suction effects by tree roots

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Abstract

Strengthening soft and weak soil via root reinforcement is a well known strategy that is adopted worldwide. In Australia, native gum trees remain evergreen throughout the year and have been utilised to stabilise transportation corridors via reinforcement provided by the roots and the suction generated within the root domain as a function of evapo-transpiration through the canopy. A mature gum tree can induce a massive total suction pressure exceeding 30 MPa through its root water and solute uptake in terms of matric plus osmotic suction. This cumulative effect of matric and osmotic suction contributes to the overall shear strength of the soil, but the significant osmotic suction is often ignored in classical geotechnical engineering that does not consider the presence of trees. This study is an attempt to demonstrate the important role of osmotic suction, because it is directly proportional to the solute concentration in the soil and the solute uptake mechanisms of the surrounding vegetated ground.

Keywords chosen from ICE Publishing list

Geotechnical engineering; Mathematical modelling

List of notation

S	is the rate of root water uptake
β	is the root density
β_{max}	is the maximum root density
T_P	is the potential transpiration
ψ	is the total suction
ψ_m	is the matric suction
ψ_π	is the osmotic suction
k_1, k_2	are empirical coefficients
k_3, k_4	are experimental coefficients
V	is the total volume
r_{max}	is the horizontal distance from tree trunk to maximum root density
z_{max}	is the vertical distance from surface to maximum root density
ψ_{an}	is the lowest value of ψ at maximum S
ψ_d	is the highest value of ψ at maximum S
ψ_w	is the soil suction at wilting point
S^*	is the modified S with osmotic suction
S_s	is the solute uptake
C	is the sum of the molar concentrations of anions and cations in the solution
θ	is the volumetric moisture content
k	is the hydraulic conductivity
k_s	is the saturated coefficient of permeability

a	is the salinity threshold expressed as a pressure
b	is the slope expressed in percentage per kilo Pascal
R_e	is the retardation coefficient
D	is the diffusion coefficient
v	is the Darcy velocity
R	is the universal gas constant
T	is the absolute temperature

1. Introduction

Using native trees to stabilise soft soil is an attractive method of ground improvement that is becoming increasing popularity in Australia. There are many engineering solutions for stabilising soil, such as geosynthetic liners, vertical drains (Indraratna *et al.*, 2000) and chemical additives (i.e. lime, lignosulfonate). Reinforcement by tree roots is another popular and well established method that is practiced around the world. Previous studies discovered that larger roots provide anchorage while the smaller roots can increase the apparent cohesion of soil to increase its strength (Docker and Hubble, 2001, Norris and Greenwood, 2000, Areghan *et al.*, 2015). Docker and Hubble (2001) also carried out field tests at Camden valley, NSW, Australia, and found that at 10% shear strain the roots provided 20-40% of shearing resistance. Apart from the effect of root reinforcement, soil suction also helps to strengthen soft soil (Fatahi *et al.*, 2007; Indraratna *et al.*, 2006).

Evapotranspiration induces root water uptake and dissipates excess pore water pressure from the root zone, which then increases the matric suction in the neighbouring soil. Root water uptake and transpiration are mainly governed by the species of trees (root growth rate, distribution, and canopy area), the type of soil (soil suction and hydraulic conductivity, etc.) and the atmospheric conditions (temperature and humidity). In this study we considered root distribution with specific reference to the maximum root density zone, the soil suction, and potential transpiration.

Soil suction consists of matric and osmotic suction, where osmotic suction is generally omitted in unsaturated soil mechanics. Most conventional methods ignore the effect of osmotic suction sustained as a result of the solute concentration (including the changes of nutrient levels) in the soil. Therefore, the approach proposed in this paper focuses more on the changes in osmotic suction near the root zone of a tree governed by the nutrient uptake. Changes in the concentration of pore fluid change the inter particle repulsive forces and the thickness of the double diffusive layer (Barbour, 1987). These changes in the repulsive forces can be calculated through osmotic suction using van't Hoff's approximation (Barbour, 1987), and therefore evaluating variations in osmotic suction over time is important in geotechnical engineering projects that include native trees. Osmotic suction stems from the solute uptake by roots that create a concentration gradient around the root zone, and solute transport near the root zone occurs by mass flow and molecular diffusion where nutrients/salts are absorbed by roots only in their dissolved form in pore water (Simunek and Hopmans, 2009); therefore, when solute uptake commences there is a subsequent concentration gradient. This concentration gradient causes the solutes to diffuse towards the root zone from neighbouring soil. Solute uptake is classified as passive and active, where passive uptake defines mass uptake through root water uptake, and active uptake accounts for all other means such as energy-driven mechanisms due to electromagnetic gradients (Simunek and Hopmans, 2009). This current study only captures the passive solute uptake by roots to minimise an otherwise complex problem.

Evapotranspiration and the associated root water/solute uptake are highly subjective to the species of trees, the types of soil, and the atmospheric conditions. Plant physiologists and botanists have provided more complex studies in literature that combine the effects of plant metabolism and extra nutrient uptake due to mycorrhizae (fungal activity) (Marschner, 1995). This current study is an attempt to modify the current governing equations to capture the effect of total suction, while ignoring the effect of atmospheric conditions such as rainfall, drought, and seasonal changes. The model proposed in this paper aims to estimate the root water uptake that is influenced by the tree roots while capturing the role of matric and osmotic suctions. In contrast, the earlier model proposed by Indraratna *et al.*, (2006) enables the estimation of the root water uptake based on the associated matric suction, but it does not consider the effect of the osmotic suction.

2. Theoretical model formulation

The root water uptake model used by Indraratna *et al.*, (2006) has been extended in this study. Equation 1 shows the root water uptake with respect to root density function ($G(\beta(t))$), Potential transpiration ($F(T_P(t))$) and root uptake reduction factor influenced by matric suction ($f(\psi_m)$) (Fatahi *et al.*, 2010). For instance, in Indraratna *et al.*, (2006) the root water uptake rate ($S(r, z, t)$) is described by a function of the maximum possible root water uptake and by the root water uptake reduction factor ($f(\psi_m)$), which is a function of soil matric suction (Figure 1). The root uptake reduction factor considers the level of ease in which the tree draws water from the soil, i.e. at low soil suction the tree root uptake is optimal whereas for soil suction values approaching the wilting point (ψ_w), the tree experiences increasing difficulty to extract water, and eventually ceases to do so at the wilting point (Figure 1). The maximum root water uptake can be estimated based on the root density and the potential transpiration distributions ($G(\beta(t))F(T_P(t))$). This is expressed in Eq. 1 as follows.

$$S(r, z, t) = G(\beta(t))F(T_P(t))f(\psi_m(t)) \quad (1)$$

where,

$$\beta(r, z, t) = \beta_{\max}(t)e^{-k_1|z-z_0(t)|-k_2|r-r_0(t)|} \quad (2)$$

For which the root density distribution $G(\beta)$ is obtained as follows,

$$G(\beta) = \frac{\tanh(k_3\beta)}{\int_{V(t)} \tanh(k_3\beta) dV} \quad (3)$$

Similarly, the potential transpiration function is expressed as follows,

$$F(T_P) = \frac{T_P(1 + k_4 z_{\max} - k_4 z)}{\int_{V(t)} G(\beta)(1 + k_4 z_{\max} - k_4 z) dV} \quad (4)$$

The root water uptake reduction factor function $f(\psi_m)$ shown in Eq. 5 is graphically represented in Figure 1.

$$\left. \begin{aligned} f(\psi_m) &= 0 & \psi_m < \psi_{an} \\ f(\psi_m) &= 1 & \psi_{an} \leq \psi_m < \psi_d \\ f(\psi_m) &= \frac{\psi_w - \psi}{\psi_w - \psi_d} & \psi_d \leq \psi_m < \psi_w \\ f(\psi_m) &= 0 & \psi_w \leq \psi_m \end{aligned} \right\} \quad (5)$$

In Equation 1, Indraratna *et al.*, (2006) only includes the effect of matric suction to account for the pressure head, however, the osmotic suction related to solute uptake by tree roots in the root water uptake model must be considered, so van Genuchten (1987) proposed an expanded formulation for the total suction, as given by Equation 6.

$$S^*(r, z, t) = G(\beta(t))F(T_P(t))f(\psi(m, \pi)) \quad (6)$$

Therefore, in this study a threshold-slope function proposed by Mass and Hoffman (1977) is used to incorporate osmotic suction, as shown in Equation 7. The root water uptake reduction factor incorporating the effect of osmotic suction, given in Eq. 7 is graphically illustrated in Figure 2.

$$\left. \begin{aligned} f(\pi) &= 1 & 0 \leq \pi \leq a \\ f(\pi) &= 1 - b(\pi - a) & a < \pi < a + 1/b \\ f(\pi) &= 0 & a + 1/b \leq \pi \end{aligned} \right\} \quad (7)$$

Total suction can be calculated as either an additive or a multiplicative model in Equation 6. In this current study the additive model is used. The term modified in this study was the root uptake reduction factor to incorporate the effect of osmotic suction. This implies that the level of ease in which the tree draws water from the soil is both governed by matric suction as well as osmotic suction, given in Eq. 8, as follows,

$$f(\psi) = f(\psi_m) + f(\psi_\pi) \quad (8)$$

The interaction between soil and water at the root zone is treated as a continuous media, where the root water uptake is included as a sink term in the flow continuity equation (Equation 9) (Indraratna *et al.*, 2006, Shouse *et al.*, 2011).

$$\frac{\partial \theta}{\partial t} = \nabla (k \nabla \psi_m) - \frac{\partial k}{\partial z} - S \quad (9)$$

To calculate the associated changes in matric suction induced by a variation of volumetric water content influenced by the root water uptake, a simple empirical relationship proposed by Fredlund and Xing (1991) was adopted. The water retention behaviour was modelled considering the soil index properties (i.e. wPI, weighted plasticity index) as suggested by Zapata et al. (2000). While, the compared sites found in literature do not provide exact information about the soil water retention behaviour of the field soils, the majority of the soils can be classified as CH (Table 2) and wPI of 50 is assumed. This constitutes a limitation of the current study. For calculating the variation of osmotic suction in the soil induced by nutrient uptake, a more rigorous analytical procedure is outlined subsequently.

In this current study the passive solute uptake is considered where the solute concentration is multiplied by the root water uptake (Simunek and Hopmans, 2009).

$$S_s = CS^* \quad (10)$$

In the same manner as shown in Equation 9, solute uptake by roots can be incorporated into the advection dispersion equation via a sink term, as shown in Equation 11.

$$\frac{\partial(\theta R_e C)}{\partial t} = \nabla \left(\theta D \frac{\partial C}{\partial z} - vC \right) - S_s \quad (11)$$

Osmotic pressure can be calculated through van't Hoff's approximation (Equation 12).

$$\psi_\pi = RTC \quad (12)$$

Therefore, the change in osmotic suction can be calculated from Equation 13.

$$\frac{d\psi_\pi}{dt} = RT \frac{dC}{dt} \quad (13)$$

In most previous studies the sink term which captures the solute uptake and associated osmotic suction has been ignored (Bresler and Hoffman, 1986, Shouse *et al.*, 2011), whereas in this study, the sink term is captured in simulations to obtain a more reliable answer for total suction. The finite element program ABAQUS is adopted to simulate the above mentioned theoretical model. The sink terms in Equation 9 and 11, i.e. the rate of root water uptake and solute uptake are included into ABAQUS through PYTHON subroutines. Figure 3 shows the finite element mesh of 5496 nodes and 11077 elements that correspond to finite element sizes of 0.2 m and 0.7 m at the

root zone and the remainder of the soil, respectively. A linear pressure distribution was assumed for matric suction from top (600 kPa) to bottom (400 kPa) as the initial condition (Indraratna *et al.*, 2006). A finer mesh is used for the root zone to obtain a more refined output, because all the above equations are applied in this zone. Table 1 outlines all the model parameters adopted. The boundary conditions adopted are also shown in Figure 1.

The results obtained from the proposed model are compared to the field data reported in Jaksa *et al.*, (2002) and Potter (2005). Jaksa *et al.*, (2002) presented variations of total suction in the vicinity of a large gum tree in Holden Hill site, South Australia, while Potter (2005) reported different species of gum trees and associated suction profiles (total, matric and osmotic) for Victorian and Queensland soil. Jaksa *et al.*, (2002) measured the total suction by means of transistor psychrometer, whereas Potter (2005) used the filter paper method for measuring the total and matric suction. Therefore, in the latter, the osmotic suction was calculated by the difference between the total and matric suctions. Moreover, the calculated osmotic suction was cross-checked with the electrical conductivity method in some locations.

Field data from the Miram site, the Horsham site, the Emerald site, and the Wal Wal site are from a gum tree approximately 3 m, 4 m, 7 m, and 12 m away, respectively. The salinity levels and salt tolerance of these gum trees vary from place to place such that the salinity tolerance is 50-100 mS/m in Victoria (Marcar *et al.*, 2000), and 800-1000 mS/m in Queensland (House *et al.*, 1998). Unfortunately, the compared sites found in literature, do not provide exact information about the salinity or the solute concentrations in the soil for the authors to further exemplify and reiterate the importance of soils properties, and this is a limitation of the current study.

Therefore, an average of 500 mS/m of salinity was used for simulations in the current study. In Equation 7, the parameters a and b are adjustable (Shouse *et al.*, 2011), and they were assumed to be 832 kPa (corresponding to a salinity level of 1000 mS/m) and 5%, respectively. The longitudinal dispersivity was assumed to be 0.02 m with a diffusion coefficient of $1.33 \times 10^{-9} \text{ m}^2/\text{s}$. For simplicity the same root geometry was adopted for all case studies, as this was not reported in the field studies considered. This is reasonable, as the majority of the trees considered (Table 2) are Australian mature gum trees (*Eucalyptus*). Further details in relation to the initial conditions and the site characteristics of the case studies adopted are listed in Table 2.

2. Results and discussion

Figure 4 shows the result for changes in the concentration of solute after a 1 year simulation where this change was used to calculate changes in osmotic suction (Figure 5) using Equation 13. Average values from the field data reported in Potter (2005) are compared with the calculated values for osmotic suction in Figure 5, where the results fundamentally agree but are not a perfect match because different field conditions and different species of gum trees are compared with the model predictions. For instance, maximum root density ($r_{0,z0}$) in the model is 7 m from the tree trunk and 3 m from surface, whereas the maximum root density is not reported for the field data

reported in Potter (2005). Moreover, it was assumed that all the gum trees reported in field data had the same root distribution as the model, while only average field values for osmotic suction at depths of 1 m, 3 m, and 4 m are plotted to compare with model predictions. While the model performance for distances from the tree trunk smaller than 5m and greater than 10m is reasonable, unfortunately, no field data was reported for the location assumed to correspond to the maximum root density (7m, 3m) which would yield peak osmotic suction changes. This is a limitation of the current study.

Figure 6 ,modified from Indraratna *et al.*, (2006), shows the model predictions for matric suction computed based on the root water uptake rate (Eq. 1) and considering the water retention behaviour (Zapata *et al.*, 2000) based on the soil wPI. It was evident that the maximum change in matric suction occurred at the maximum root density of (7 m, 3 m) due to the maximum root water uptake after a 1 year simulation. Solute uptake is considered to be a simultaneous activity of the root water uptake, as given by Equation 10, and therefore the solute uptake is also maximum at the maximum root density (Figure 5). Thus, the change in concentration and associated change in osmotic suction is higher near the maximum root density zone due to the diffusion of solutes close to the maximum root density zone, which creates a concentration gradient and increases the change in osmotic suction, as shown in Figures 4 and 5, respectively. Moreover, the salts that adhere to the particles of soil are buffering, an action that is captured through the retardation coefficient (R_e) in Equation 11.

Figure 7 shows a summary of the changes in matric suction from Indraratna *et al.*, (2006) and the changes in osmotic suction from the current study. Total suction is also compared to the field data by Jaksa *et al.*, (2002) and Potter (2005) for different depths. As with the discussion in Figure 5, the changes in total suction also agree with the averaged field data subjected to field variables and different species of gum trees. There is an increase in the change in total suction towards the maximum root density and a gradual decrease away from it. These model predictions show promising results for increasing the total suction in the subsurface by water, and solute uptake by tree roots. The model presented herein provides an estimation of the root water uptake that is blatantly influenced by the tree roots. However, it is important to note that while the soil properties certainly influence the soil-water retention behaviour, they do not directly influence the root water uptake mechanism. Moreover, native gum trees in Australia have proven their suitability for stabilising soft soil, and thus can be used at minimal cost for infrastructure projects around the country.

3. Practical implications

Bioengineering is an emerging technique with environmental and economic advantages for Australia and other tropical regions like South East Asia where fluctuating moisture in soft soil is a problem in landslide prone areas. As shown in this paper, native trees can increase the suction

in soil due to transpiration. Moreover, they provide root reinforcement from a well-distributed root structure, and better ground improvement can be obtained through implementing bioengineering with gabions, retaining walls, timber and concrete crib walling (Barker, 2001). Green corridor concept applied to transport corridors (i.e. railway tracks) is another practical use of native vegetation. A series of trees grown at a certain distance along a rail corridor can be useful for stabilising soft soil while gaining a more cost effective and environmentally friendly approach. Therefore, the developed model can be utilised to predict the effect of suction not only for gum trees, but also for other type of trees, provided that the tree specific parameters are properly assessed.

4. Conclusions

This paper presented a mathematical model developed for root water and solute uptake which could capture both components of matric and osmotic suction. The main parameters affecting the root uptake were root distribution, total soil suction, and potential transpiration. This mathematical model for root and solute uptake was put into ABAQUS using PYTHON subroutines; its predictions were compared to the field data available in literature and were found to be in acceptable agreement.

The change in concentration of dissolved salts was used to calculate the change in osmotic suction, and this provided a reasonable comparison with field data. Therefore, the total suction was calculated using the model predictions and matric suction results available in literature. The maximum change in total suction was obtained at the maximum root density zone (7 m, 3 m) because of the increase in matric suction due to root water uptake and diffusion of solutes from the neighbouring soil, along with the desorption of salts from soil due to the effect of buffering took place from solute uptake. However, the model predictions were not in complete agreement with the field data, because of the limited number of parameters available in literature.

Although the model needed precise field data, the mathematical sequence and numerical approach presented within this study is a promising methodology for predicting the total suction near a root zone. The authors believe that this model would facilitate an interest in promoting native vegetation to stabilise soft soil in transport corridors and infrastructure development.

These high levels of suction (up to 4500 kPa) generated by tree root osmosis are far above than typical suction pressures that can be applied using conventional vacuum equipment (maximum 100 kPa) for soil stabilisation. Therefore, the concept of green corridors for stabilising transport lines built over relatively soft ground will carry significant benefit in a technical sense, apart from the obvious environmental and aesthetic aspects.

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Table 1. Model parameters collected from literature

Table 2. Summary of the initial conditions and site characteristics for the case studies adopted

Table 1. Model parameters

Parameter	Value	Reference
$\beta_{\max}$	25 m ⁻²	Indraratna <i>et al.</i> , (2006)
k_1	1.5	Knight (1999)
k_2	2	Knight (1999)
r_0	7 m	Indraratna <i>et al.</i> , (2006)
z_0	3 m	Indraratna <i>et al.</i> , (2006)
k_3	8.74 x 10 ⁻² m ⁻¹	Indraratna <i>et al.</i> , (2006)
k_4	0	Indraratna <i>et al.</i> , (2006)
T_P	9 mm/d	Dunin <i>et al.</i> , (1985)
$r_{\max}$	15 m	Indraratna <i>et al.</i> , (2006)
$z_{\max}$	9 m	Indraratna <i>et al.</i> , (2006)
ψ_{an}	4.9 kPa	Feddes <i>et al.</i> , (1976)
ψ_d	40 kPa	Feddes <i>et al.</i> , (1976)
ψ_w	3000 kPa	Indraratna <i>et al.</i> , (2006)
k_s	5 x 10 ⁻⁹ ms ⁻¹	Indraratna <i>et al.</i> , (2006)
a	832kPa	
b	5%	

Table 2. Summary of the initial conditions and site characteristics for the case studies adopted

Parameter	Case study 1 (Potter, 2005)	Case study 2 (Potter, 2005)	Case study 3 (Potter, 2005)	Case study 4 (Potter, 2005)	Case study 5 (Jaksa et al., 2002)
Site location	Miriam site (Victoria)	Horsham site (Victoria)	Wal Wal site (Victoria)	Emerald (Queensland)	Holden Hill (South Australia)
Soil classification (USGS)	CH	CH	SM /CL	CL / CH	CH
Tree species (Gum trees)	Blackbox (<i>Eucalyptus largiflorens</i>)	Red gum (<i>Eucalyptus camaldulensis</i>)	Sugar Gum (<i>Eucalyptus cladocalyx</i>)	<i>Brigalows</i> (<i>Acacia harpophylla</i>)	Spotted gum (<i>Eucalyptus maculata</i>)
Approximate height of the tree (m)	7	15	10	10	20
Suction measurements	Total and matric : Filter paper method				Total: transistor psychrometer

Figure captions

Figure 1. Root water uptake reduction factor $f(\psi_m(t))$ considering matric suction (after Indraratna et al., 2006).

Figure 2. Root water uptake reduction factor $f(\pi)$ considering osmotic suction.

Figure 3. (a) Schematic sketch of the soil-tree system and (b) finite element mesh for the root zone and the soil.

Figure 4. Change in solute concentration

Figure 5. Change in osmotic suction with distance away from the tree trunk

Figure 6. Change in matric suction (modified after Indraratna et al., 2006)

Figure 7. Total suction with distance away from the tree trunk

Figure 1. Root water uptake reduction factor $f(\psi_m(t))$ considering matric suction (after Indraratna et al., 2006).

Rate of Root Water Uptake (S)

Figure 2. Root water uptake reduction factor $f(\pi)$ considering osmotic suction.

Osmotic suction reduction factor $f(\pi)$

Figure 3. (a) Schematic sketch of the soil-tree system and (b) finite element mesh for the root zone and the soil.

A (root zone)

B (at inters

Figure 4. Change in solute concentration

Figure 4. Change in solute concentration

Figure 5. Change in osmotic suction with distance away from the tree trunk

Figure 5. Change in osmotic suction with distance away from the tree trunk

Figure 6. Change in matric suction (modified after Indraratna et al., 2006)

Figure 6. Change in matric suction (modified after Indraratna et al., 2006)

Figure 7. Total suction with distance away from the tree trunk

Figure 7. Total suction with distance away from the tree trunk