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Conceptual Development and Numerical Modelling of Vegetation Induced Suction and implications on Rail Track Stabilisation

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Keywords: root water uptake, numerical modelling, suction, rail track, native vegetation

ABSTRACT: The effects of tree roots on soil suction and ground settlement are investigated. This paper highlights the inter-related parameters contributing to the development of a conceptual evapo-transpiration and root water uptake equilibrium model that is then incorporated in a comprehensive numerical model. The developed numerical model based on the finite element analysis (ABAQUS) considers fully coupled flow-deformation behaviour of soil. Field measurements obtained by the authors from a field site in western Victoria and from past literature are used to validate the model. The predicted results show acceptable agreement with the field data in spite of the assumptions made for simplifying the effects of soil heterogeneity and anisotropy. The numerical analysis proves that the proposed root water uptake model can reliably predict the region of maximum matric suction away from the tree axis. The paper also compares the natural favourable effect of tree roots with the stabilising mechanisms of geosynthetic vertical drains subjected to vacuum pressure. Although this analogy is only justified for shallow vertical drains, the comparison still emphasises the obvious economical advantages of native vegetation.

1 Introduction

Tree roots provide three independent stabilising functions: (a) reinforcement of the soil, (b) dissipation of excess pore pressure and (c) establishing matric suction increasing the soil shear strength. The matric suction established in the root zone propagates radially and contributes to ground stabilisation near the root zone. Using native vegetation in semi-arid climates and coastal regions of Australia has become increasingly popular for stabilising railway corridors built over expansive clays and compressive soft soils. As a consequence of passage of heavy trains or ballast tamping to reshape and level the ballast, a ballast bowl (or ballast pocket) in which water accumulates and softens the ground can be formed under the track granular layer. Using native vegetation can be a cost effective and environmentally friendly solution to remediate this problem.

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 instance, Fredlund and Hung (2001) in their analysis to predict volume change due to presence of vegetation in expansive soils, did not consider a reasonable root zone. It was assumed that the root water uptake rate is time-independent, which is far too over simplified. 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. Biddle (1998) did not report the effects of root distribution. Many attempts (e.g. Cameron, 2001; Jaksa et al., 2002; 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 aim of this paper is to develop an integrated transient model that considers the extraction of soil water by tree roots within the vadose zone to simulate ground physical behaviour in the vicinity of tree roots. The paper consists of developing a new root water uptake model implemented in a numerical program for analysing the interaction between vegetation and soil, as well as validation of the model using field and laboratory data. The natural effects of planting trees along the railway corridors are also compared with the effects of prefabricated vertical drains with vacuum preloading.

2 Root water uptake model

The available water content of a soil-vegetation system can be estimated as:

$$W = W_0 + I - O \tag{1}$$

where, W is the available amount of water in the soil system, W_0 is the initial amount of water content, I is the quantity of water entering the soil system, and O is the quantity of water leaving the soil system, mostly through evapo-transpiration. According to Blight (2003) the evapo-transpiration is probably the most uncertain and difficult term to evaluate in the soil water balance. 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.

The details of each single root and its interaction with the surrounding soil is required to identify the microscopic interaction between the soil and root system (Figure 1). In this study a macroscopic approach is adopted, which considers the integrated properties of the entire root system. Therefore, the root water uptake is considered as a volumetric sink term in the flow continuity equation, which can be defined as the volume of water extracted per unit bulk volume of soil per unit time. The soil water flow differential equation, including the sink term, $S(x, y, z, t)$, can then be written as:

$$\frac{\partial \theta}{\partial t} = \nabla.(k\nabla \psi) - \frac{\partial k}{\partial z} - S(x, y, z, t) \tag{2}$$

where, θ is the volumetric moisture content, ∇ is the divergence vector, ψ is the soil suction, k is the hydraulic conductivity, and z is the vertical coordinate.

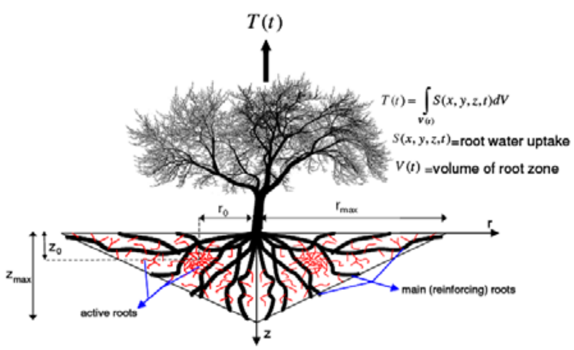

Figure 1. Schematic sketch of soil-plant-climate system.

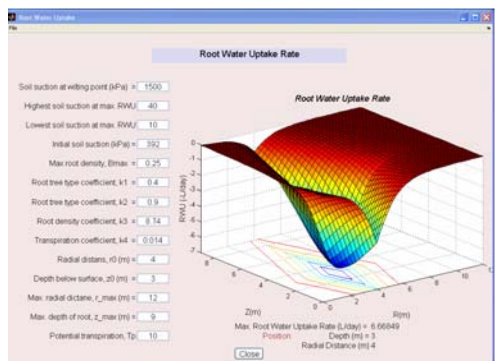

Figure 2. A typical example of the distribution of initial rate of root water uptake.

Indraratna et al. (2006) have developed a mathematical model for the distribution of tree root water uptake within the root zone. This proposed model combines the effects of soil matric suction, root density and potential transpiration rate. Consequently, the rate of tree root water uptake can be formulated as:

$$S(x, y, z, t) = f(\psi)G(\beta)F(T_P) \tag{3}$$

where, $f(\psi)$ is the soil suction factor, $G(\beta)$ is the root density factor, and $F(T_P)$ is the potential transpiration factor. As discussed by Indraratna et al. (2006), the relationship between $f(\psi)$ and soil suction suggested by Feddes et al. (1974, 1978) can be an appropriate function for implementing in the root water uptake model. This relationship can be written as:

$$\left\{\begin{array}{ll} f(\psi) = 0 & \psi < \psi_{an} \\ f(\psi) = 1 & \psi_{an} \le \psi < \psi_d \\ f(\psi) = \dfrac{\psi_w - \psi}{\psi_w - \psi_d} & \psi_d \le \psi < \psi_w \\ f(\psi) = 0 & \psi_w \le \psi \end{array}\right\} \tag{4}$$

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 is the highest value of suction and ψ_{an} (soil suction at anaerobiosis point) is the lowest value of suction at the maximum root water uptake rate.

Equations (5) and (6) are suggested by the authors for the root density factor and potential transpiration factor, respectively.

$$G(\beta) = \frac{\tanh(k_3 \beta_{\max} e^{-k_1|z-z_0|-k_2|r-r_0|})}{\int_{V(t)} \tanh(k_3 \beta_{\max} e^{-k_1|z-z_0|-k_2|r-r_0|}) dV} \tag{5}$$

$$F(T_P) = \frac{T_P(1 + k_4 z_{\max} - k_4 z)}{\int_{V(t)} G(\beta)(1 + k_4 z_{\max} - k_4 z) dV} \tag{6}$$

where, 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 the vertical coordinate, r is the radial coordinate, $\beta_{\max}$ is the maximum density of root length 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 involve depth on the potential transpiration distribution, and $V(t)$ is the volume of the root zone at time t. These equations have been fully elaborated in Indraratna et al. (2006). Discussion about the influence of above parameters on the rate of root water up take can be found in Fatahi (2007). Figure 2 shows a typical example of the distribution of initial rate of root water uptake for a single tree used in the finite element analysis as described in Section 4.

3 Coupled flow and deformation equations incorporating matric suction induced by tree roots

In this study, a fully coupled flow-deformation model has been developed for unsaturated soils embracing the proposed root water uptake model. The deformation model used in the governing equations is based on the continuum mechanics theories and the modified effective stress concept for unsaturated soils. The flow model is based on Darcy's law, Henry's law and the conservation of mass. The deformation and flow models are coupled through the effective stress parameters and the ABAQUS finite element code has been used to solve the equations considering the root water uptake model.

3.1 Effective stress equation of unsaturated Soils

The effective stress principle converts a multi-stress state porous medium to a mechanically equivalent single-stress state continuum, allowing the application of the principles of continuum solid mechanics to deformable porous media filled with fluid. The basic effective stress concept, Equation (7), suggested by Bishop (1959) has been adopted in this study to analyse unsaturated soil behaviour.

$$\sigma'_{ij} = \sigma_{ij} - u_a \delta_{ij} + \chi(u_a - u_w)\delta_{ij} \tag{7}$$

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. In unsaturated soil mechanics, the term $(u_a - u_w)$ is called the matric suction. The two main arguments, which are often cited in literature, are that the effective stress theory in unsaturated soils cannot explain the collapse that occurs in unsaturated soils and that there is no unique relationship between χ and the degree of saturation. Khalili and Loret (2001) have shown that plastic deformation such as collapse can be readily described within the effective stress framework by defining the yield surface as a function of suction. Although much criticism of Equation (7) has been made because of the uncertainty of the value of χ, which depends on a number of factors such as degree of saturation, soil type and hysteresis effects, Khalili and Khabbaz (1998) showed that by plotting the value of χ against a more appropriate parameter such as suction ratio (matric suction over the air entry value), a unique relationship can be obtained for most soils, which have been used in this research.

$$\chi = (\psi_e / \psi)^{0.55} \quad for \quad \psi \geq \psi_e \tag{8}$$

where ψ is the matric suction and ψ_e is the air entry value i.e. the matric suction value making the transition between saturation and unsaturation states. It can be noticed that for $\psi < \psi_e$, $\chi = 1$.

3.2 Effective stress Equation of unsaturated Soils

According to Khabbaz (1997), the water phase and air phase equations can be coupled with the effective stress and compressibility coefficients. The following differential equations present the coupled flow and deformation equations considering the root water uptake model using the effective stress theory in the elastic region.

$$G\frac{\partial^2 u_i^{\,e}}{\partial x_i \partial x_j} + (\lambda + G)\frac{\partial^2 u_j^{\,e}}{\partial x_i \partial x_j} + \chi\left(\frac{\partial u_w}{\partial x_i} - \frac{\partial u_a}{\partial x_i}\right) + \frac{\partial u_a}{\partial x_i} + F_i = 0 \tag{9}$$

$$\frac{1}{\gamma_w}\nabla.(k_w \nabla u_w) - \frac{\partial k_z}{\partial z} - G(\beta)F(T_p)\, f(\psi) = (1-\chi-\phi_a)c_m\left(\frac{\partial u_w}{\partial t} - \frac{\partial u_a}{\partial t}\right) - \chi\frac{\partial}{\partial t}(\nabla u_i) \tag{10}$$

$$\frac{1}{\gamma_a}\nabla.(k_a \nabla u_a) - \frac{\partial k_a}{\partial z} = \frac{\phi_a}{P}\frac{\partial u_a}{\partial t} + (1-\chi-\phi_a)c_m\left(\frac{\partial u_a}{\partial t} - \frac{\partial u_w}{\partial t}\right) - (1-\chi)\frac{\partial}{\partial t}(\nabla u_i) \tag{11}$$

where G and λ are Lame's constants, F_i is the body force per unit volume, c_m is the compressibility coefficient ϕ_a is the air porosity, k_a and k_w are the air and water permeability coefficients, and P is the absolute pressure. If the soil behaviour is in the plastic region, Equation (9) is modified by the hardening and flow rule of plasticity, to calculate the plastic strains on the yield surface as explained in detail by Fatahi (2007).

4 Solution procedures based on numerical analysis

Achieving exact solutions of the highly non-linear differential equations developed for coupled flow and deformation models is very difficult, hence, an approximate solutions based on the finite element method is the most appropriate approach. For the numerical analysis of the proposed coupled flow-deformation equations, ABAQUS 6.5 has been used, as, this program is a flexible tool for multi media analysis and can accommodate unsaturated soil properties. An important aspect of ABAQUS software is the ability to write subroutines to modify the existing models. Several user subroutines have been written in FORTRAN included in the program for executing the analysis. As mentioned above, these analyses are highly non-linear mainly because the unsaturated permeability coefficients and the rate of root water uptake change with the pore pressures and void ratio of the soil at each time step. In this study the coefficient of soil permeability, k , described by Brooks and Corey (1966) is used:

$$k = k_s S_e^{\frac{2+3\lambda}{\lambda}} \tag{12}$$

$$S_e = \frac{S_r - S_{ru}}{1 - S_{ru}} \tag{13}$$

where, k_s is the saturated coefficient of permeability estimated based on the Kozeny-Carman equation, S_e is the effective degree of saturation, S_r is the degree of saturation, S_{ru} is the residual degree of saturation, and λ is the slope of the soil water characteristic curve. The Kozeny-Carman semi-empirical formula for predicting the saturated permeability of porous media can be written as:

$$k_s = \frac{\gamma}{C_{KC}\,\mu S_0^2}\frac{e^3}{1+e} \tag{14}$$

where, γ is the unit weight of the fluid, μ is viscosity of the fluid, C_{KC} is Kozeny-Carman empirical coefficient, S_0 is the specific surface area per unit volume of particles and e is the void ratio of the porous media. The above permeability equations in conjunction with the soil water characteristic curve of the soil are included in the ABAQUS input file.

The effects of permeability coefficient variation, root density distribution, soil suction and potential transpiration have been incorporated in the flow equation as a sink term. The root water uptake model has been considered in the finite element analysis using the flow subroutines. These flow subroutines allow the user to apply the sink term on any nodes or elements of the model to simulate the discharge of moisture from the soil medium due to evapo-transpiration. Conducting the proposed finite element analysis, displacements, pore pressures, and boundary reactions can be obtained at any time step. As the soil properties depend on their state of stress, the stiffness matrix is recalculated at the end of each time step with revised material properties.

5 Model verification

The model proposed for the rate of root water uptake was included in the numerical analysis using the ABAQUS finite element program to examine the distribution of soil suction and profile of the moisture content near a single tree. The field investigations were conducted near a black box tree (eucalyptus largiflorens), located in Miram village in western Victoria. Black box tree is a common evergreen Australian native tree. It is approximately 10-20m high and 7.5-15m in spread with rough bark on trunk and branches. The field measurements included drilling 10 bore holes to take samples, cone penetration tests to measure soil stiffness and the excavation of three trenches to observe root distribution under the ground in different directions (Figures 3 and 4). The results of the numerical results for the matric suction and moisture content around the tree were compared with the field data taken in May 2005 and April 2006.

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 as shown in Figure 5. It was also shown that the 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. Although more field data will assist in further verification of the root water uptake model, the proposed model and the associated numerical analysis is a promising tool for predicting matric suction induced by tree roots within a soil matrix.

Figure 3. Excavation around the black box tree in Miram site, Victoria for field observation.

Figure 4. A photograph of the excavated trench to observe the tree root pattern and distribution.

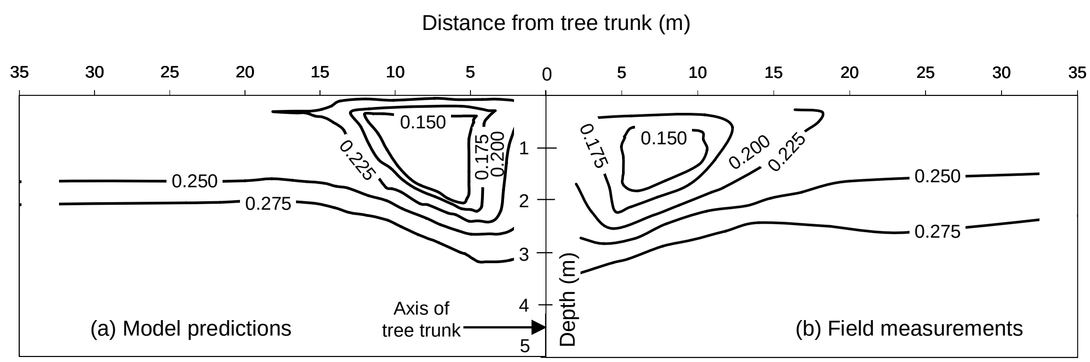

Figure 5. Contours of volumetric soil moisture content in the vicinity of the black box tree in western Victoria, Australia (a) current numerical analysis results, (b) field measurements in May 2005.

Although the root water uptake model developed in conjunction with the numerical model has been validated using field and laboratory measurements as explained earlier, further validation were conducted based on field measurements, available in literature for a single tree and a row of trees. Among them, a case history reported by Biddle (1998) is explained in this paper, which is related to the effects of tree root suction around a single, 20m high Poplar tree in Cambridge, UK. The tree was located in an area of mown grass on Gault clay. As reported by Biddle (1998), all soil moisture measurements were conducted using a neutron soil moisture gauge. A proper mesh and element geometry and boundary conditions of the finite element model was proposed to be built in ABAQUS program. For this purpose, a two-dimensional plane strain mesh employing 4-node bilinear displacement and pore pressure elements (CPE4P) was considered. Because of symmetry, a zero flux boundary was applied along the left boundary. 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.

The finite element analysis was conducted in two stages: (i) geostatic and (ii) consolidation. The first stage was to ensure that the analysis commences from a state of equilibrium under geostatic loading. The consolidation stage was to avoid non-physical oscillations and possible divergence problems caused by non-linearity behaviour. This stage included a transient analysis of partially saturated soil under transpiration, starting with 1-day intervals and then was continued for five months.

Figure 6 shows a comparison between the field measurements reported by Biddle (1998) and the numerical predictions for reduction in ground moisture content. Numerical analysis results based on the authors' model for root water uptake are in acceptable agreement with the field measurements. It is important to note that in the numerical analysis, root water uptake as a sink term were considered in the flow equation; however, the effect of each root was not taken into account individually. As the main roots penetrated into the soil, there might be a gap between them, which could lead to water collecting in the gap. Since the woody roots were in a denser pattern under the trunk and in close proximity, a disparity between the field measurements and predictions in this area would seem more likely. Furthermore, the actual field data was probably influenced by the soil heterogeneity.

Having calculated the moisture content variation, the development of matric suction can be predicted reasonably well using the soil water characteristic curve. Figure 7 shows the predicted matric suction profile after 5 months of continuous transpiration. As indicated in this figure, the matric suction established in the root zone propagates radially and influences the surrounding soil, thereby contributes to the soil stability in tree's vicinity.

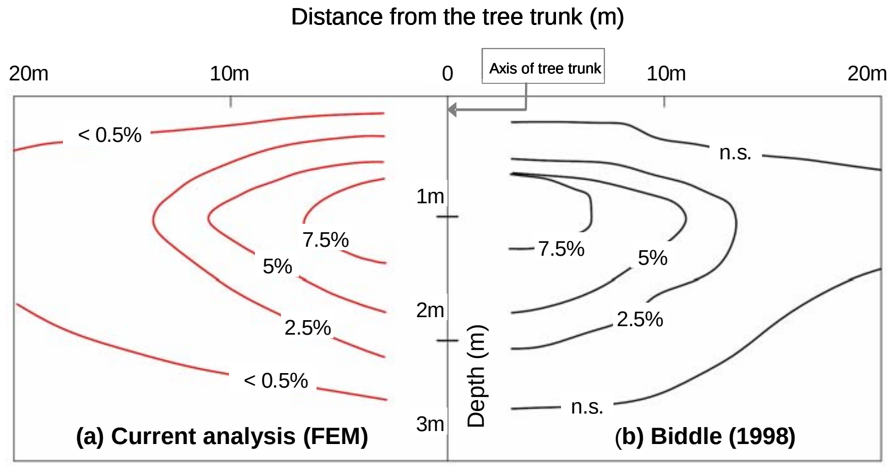

Figure 6. Contours of reduced volumetric soil moisture (%) near a Poplar tree, (a) current finite element analysis and (b) site measurements reported by Biddle (1998) [n.s. = non-significant].

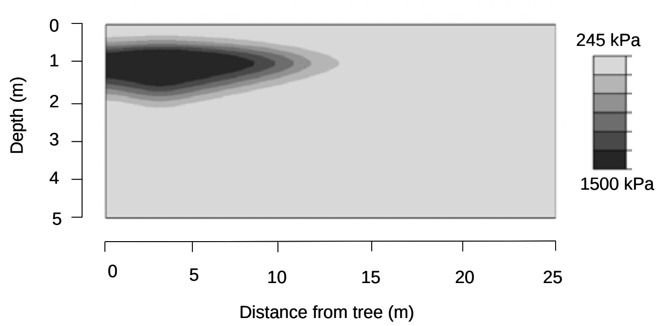

Figure 7. Predicted matric suction profile after five months, calculated in ABACUS.

6 Application

As an application of the developed model, the natural effects of planting trees along the railway corridors and the artificial effects of prefabricated vertical drains (PVDs) with vacuum preloading are compared. It is expected that the matric suction generated by natural tree roots in the root zone will be far greater than the maximum possible matric suction of 100 kPa that can be applied by vacuum pressure apparatus along the PVDs.

A two dimensional finite element analysis has been used to predict the ground displacement in the vicinity of railway lines. Firstly, the ground behaviour beneath the rail track in plane-strain conditions has been modelled. Then the effect of two rows of 11m high black box (eucalyptus largiflorens) trees on the stress-displacement behaviour of the ground under train loading has been investigated. Afterwards, the behaviour of the subgrade soil stabilised using two rows of prefabricated vertical drains with vacuum preloading along rail track has been analysed and compared with the previous case. The finite element mesh and specified boundary conditions are shown in Figure 8.

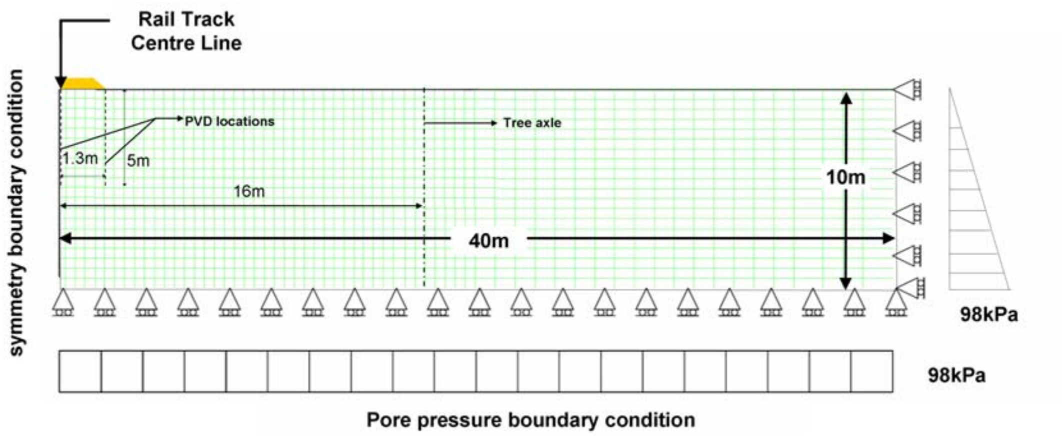

Figure 8. Geometry and boundary conditions of the finite element model.

Because of symmetry, a zero flux boundary was applied to the left hand side of mesh in Figure 8. The mesh used in this simulation contains bi-linear strain quadrilateral elements (CPE4P) with 4 displacement and pore pressure nodes at the corner of each element. The entire FE mesh consists of 4960 nodes and 4800 elements. In this study, a static load of 80 kPa with an appropriate impact factor of 1.3 has been applied in lieu with 25 tonne axle loads. In this model, the effect of a row black box trees planted 16m away from the track centre line has been simulated. In order to simulate the effect of 10m long prefabricated vertical drains with a maximum possible vacuum preloading pressure, the pore water pressure at the PVD boundaries has been set to -100 kPa. The soft soil constitutive model used in this study is an elastoplastic model using Cam-Clay failure criterion. The elastic behaviour in overconsolidated state is modelled as nonlinear and isotropic employing the following equation:

$$de^{el} = C_s \ln(\frac{p_0 + dp}{dp}) \tag{15}$$

where, de^{el} denotes the change of void ratio in the element, C_s is the swelling index, p_0 is the initial mean effective stress, and dp is the mean effective stress change on the soil skeleton.

According to Figure 9(a), the maximum root-based matric suction is 1500 kPa, which occurs away from the track centre line as the tree has been planted 16m away from the railway. Since the maximum active root density would occur away from the tree trunk on both sides of the tree, there are two zones of maximum matric suction on both sides of the tree. Figure 9(b) indicates that the maximum soil matric suction induced by vacuum preloading is only 100 kPa, which occurs between two lines of PVDs exactly underneath the rail track. In both cases, the induced soil matric suction results in the increased effective stresses and consequently soil consolidation.

Deformation in the soil profile due to the root water uptake and vacuum pressure were predicted through a coupled flow-deformation analysis. As Figure 10 illustrate, the maximum induced settlements by root water uptake and the PVDs with vacuum preloading are almost the same. However, the application of the PVDs with vacuum preloading can induce more consolidation settlement directly underneath the rail track in comparison to a row of trees 16 m away from rail track centreline. In spite of the fact that PVDs provide only 100 kPa suction, they generate more consolidation settlement than the trees. The main reason for this is that PVDs generate suction all along the drain length, but trees provide a very high suction (1500 kPa) in the root zone and mainly around the point of maximum root length density. Clearly, if trees would be planted in a much closer distance to the rail track (e.g. 2-5m), the soil would be consolidated more, but the actual roots would damage the soil formation and disturb the placing of the railway ballast affecting the internal friction. However, as the tree root zone extends more in horizontal direction in contrary to PVDs, the influence zone of trees extends more horizontally compared to PVDs.

Figure 10 shows that the vacuum induced ground surface settlement at the track centre line, which is 950 mm, is 40% more than the transpiration induced surface settlement, which is 570 mm. It means that in this case, prefabricated vertical drains with vacuum preloading can stabilise and consolidate the soil underneath the railway line almost as effectively as planting a row of black box trees 16 m away from the track centreline. It can be noted that these comparison results are related and valid for this case study with the defined initial and boundary values and assigned soil and tree parameters implemented in the analysis.

As the tree has been in place for decades, the tree root suction-based primary consolidation has already ceased. In a similar way, the vacuum assisted preloading with PVDs would be removed when the primary consolidation has ceased (>95% consolidation). Therefore, both tree roots and PVDs would initially make the soft soil settle capturing most of primary consolidation. Thus when the train load applies, the soil will behave as a stiffer soil, which causes much less track settlement. Figure 10 also shows the time-settlement curve on the soil surface at the track centreline during the treatment process prior to and after the application of the train load for different cases namely: (a) track on soft soil without any treatment, (b) track on soft soil stablised employing planting native vegetation 16 m away from the track centreline, and (c) track on soft soil stabilised with two rows of 10 m deep PVDs with 100 kPa vacuum preloading.

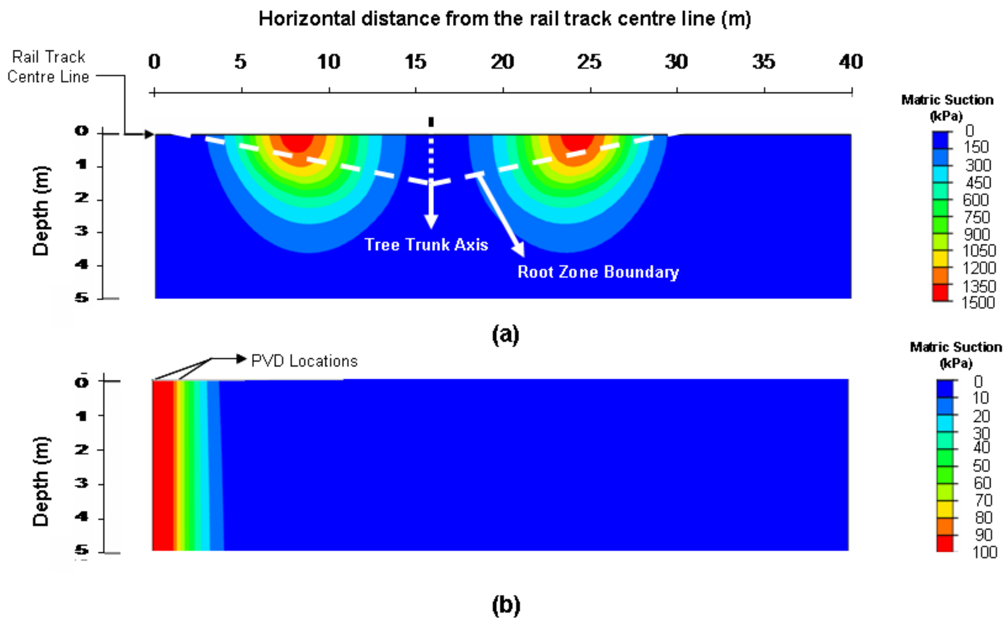

Figure 9. Contours of soil matric suction induced by (a) tree root water uptake, and (b) vacuum preloading (100kPa).

As Figure 10 shows, the main part of the primary consolidation settlement (approximately 90%) for the PVD case would be completed after about 180 days upon 100 kPa vacuum pressure application, whereas for the case of a well-developed tree this amount of consolidation takes almost 1 year of continuous transpiration. Subsequently, the trainload is assumed to be applied on the track when the soil in the vicinity of the existing trees and underneath of the rail track has already been consolidated. As shown in Figure 10, a surface settlement of 580 mm attributed to trainload of the untreated soft soil after 1000 days can be reduced to just 160 mm by planting trees along the railway line; or it can be reduced to 60 mm by ground consolidation using PVDs with 100 kPa vacuum pressure. Referring to Figure 10 it can be concluded that both the existing trees in the railway corridors and the PVDs with vacuum preloading can curtail the soft ground movements induced by the trainloads.

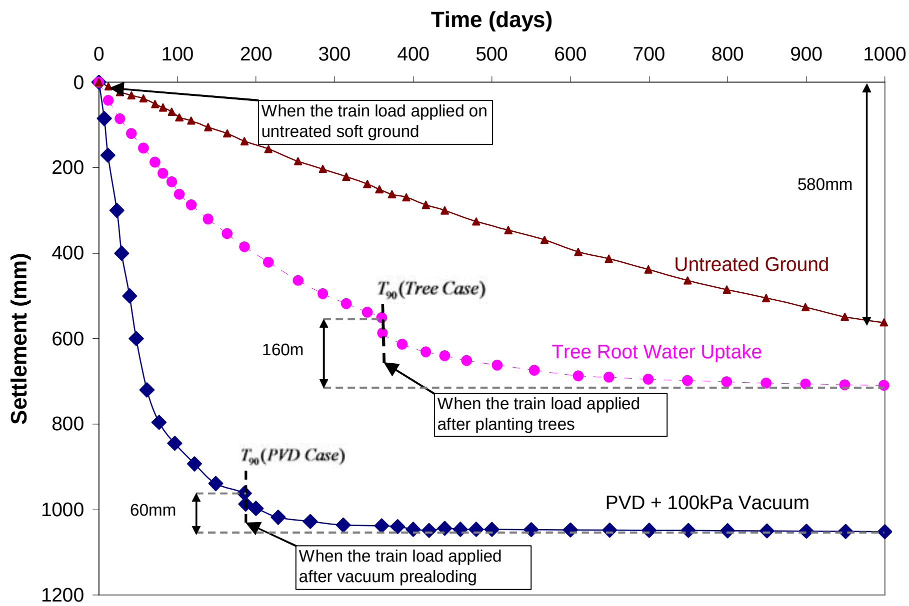

Figure 10. Time-Settlement curves during consolidation prior to and after the application of the train load.

7 Conclusions

The effects of tree transpiration on ground conditions have been examined by development of a numerical model considering the coupled flow-deformation equations. The numerical formulation can employ partially or fully saturated soil elements and is capable to capture the relationship of the unsaturated permeability and the degree of saturation at various matric suction levels. The rate of root water uptake can be predicted by the model, which takes into account soil matric suction, distribution of root density and potential transpiration. The developed model has successfully been validated using field and laboratory measurements associated with a black box tree as well as by comparing the numerical results and field data in the vicinity of a Poplar tree, reported by Biddle (1998). Despite uncertainties in an assumption of the actual distribution of tree roots, atmospheric parameters, and soil properties, there is an acceptable agreement between the measured and predicted results.

The proposed root water uptake and transpiration model verifies that the suction induced by the tree roots contributes to soft ground stabilisation. The tree roots induce sufficient drainage, dissipate pore water pressure and provide natural reinforcement for 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 organisations in Australia. Considering various soil conditions, the type of vegetation and atmospheric conditions, the proposed bioengineering model can be most useful to predict the track formation behaviour in a vegetated rail corridor.

The action of a row of trees on improving the soil behaviour has been compared to prefabricated vertical drains with vacuum pressure application. If a pattern of trees can be grown systematically along rail corridors, this may offer an inexpensive and more environmentally attractive solution to vertical drains in the long-term. It should be explained that trees need time to grow and reach to an acceptable performance situation, whereas the effect of PVDs is immediate. Results of this study demonstrate that railway infrastructure can be improved by identifying and managing surrounding vegetation – refuting the age-old belief that vegetation is detrimental to railway tracks.

8 Acknowledgements

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