Modelling of influence of matric suction induced by native vegetation on sub-soil improvement

Behzad Fatahi
University of Wollongong

CHAPTER NINE

9 CONCLUSIONS AND RECOMMENDATIONS

9.1 GENERAL SUMMARY

Population growth over the past decades has necessitated the construction of infrastructure on soft and expansive soils. One environmentally friendly methods of soil modification is the use of native vegetation to improve the shear strength and stiffness through increased suction and root reinforcement. Given the importance of the vadose zone in most geoenvironmental projects, there is a strong need to develop a better understanding of how trees, including native vegetation, affect the ground within their zone of influence.

Existing standards that are in use, such as the Uniform Building Code (1997) and Standards Australia, AS 2870 (1996), give procedures for the design and construction of footings and structures on expansive clays. None of them however provide clear guidelines on how soil suction induced by native vegetation, should be considered in design. Therefore, analysing and designing shallow foundations located in the vadose zone near native vegetation remains a challenge to geotechnical engineers.

Although it is well known that high rainfall and infiltration can rapidly reduce suction, because transpiration is a continuous process of discharging water from the soil matrix, rainfall will be quickly taken in through tree roots. Thus, in vegetated ground, the effects of matric suction on the shear strength and deformation of partially saturated soil should be considered. Moreover, as reported by Zhang et al. (2004), rainfall does not necessarily eliminate matric suction in the soil, and therefore, for a rigorous analysis, it must be incorporated into any design.

In brief, 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 formula for estimating the actual transpiration or root water uptake, the above mentioned factors have been quantified through relevant equations to develop the proposed root water uptake model. In this study, a finite element analysis was used to predict the profile of soil suction and associated ground surface settlement, based on the proposed governing equations.

The results of a numerical prediction of the matric suction and moisture around a single Black Box tree located in western Victoria, Australia, were compared with field data taken in May 2005 and April 2006. These field measurements included drilling 10 bore holes to take disturbed and undisturbed samples, cone penetration tests to measure soil stiffness and the excavation of three trenches to observe the distribution and direction of underground roots. An agreement between the measured and simulated distribution of moisture was generally obtained. It was also shown that a numerical analysis that includes the proposed model for root water uptake can reasonably predict the region of maximum matric suction away from the axis of the trunk, as field measurements show. Ground displacement contours for this case study indicated that the maximum settlement after about 3 years occurred on the surface, away from the trunk.

After this, the FEM results were compared with three published case studies to further verify the numerical predictions. In spite of uncertainties with the assumed soil parameters, root distribution and atmospheric parameters, a reasonable agreement was obtained between the measured and simulated distribution of moisture. Uncertainties in the assumed soil parameters, distribution of tree roots, and atmospheric parameters caused most discrepancies in FEM predictions and therefore, the effects of various parameters selected for the rate of root water uptake and ground displacement, have been investigated. A sensitivity analysis using the finite element method was carried out to study the influence of the parameters on ground behaviour. The findings of this study confirm that four key parameters, including permeability, wilting point suction, density and distribution of the root length, and the rate of potential transpiration must be accurately estimated or measured in order to predict the behaviour of expansive clays near tree roots.

The model developed in this study may improve the design and construction procedures for railway lines, foundations, and embankments near native vegetation, but because the influence zone of each tree may be several meters in diameter, a methodical planting of native trees along rail corridors at practical distance away, is currently being considered by rail organisations. Native vegetation that generates soil suction is comparable to prefabricated vertical drains under a vacuum, in terms of improving drainage and associated increasing the shear strength. Taking into consideration the various properties of soil, types of vegetation, and atmospheric conditions, the proposed model would be of most use in predicting the formation behaviour for rail environment.

Vegetation properly selected and used, including native trees and shrubs, can reduce moisture through root water uptake, increase the shear strength and stiffness by increasing matric suction and as a secondary effect, control erosion.

9.2 SPECIFIC OBSERVATIONS

9.2.1 Development of a new root water uptake model

1. Soil conditions (soil suction, hydraulic conductivity, and penetration resistance), type of vegetation (root distribution, the relative proportion of active roots and leaf area), and atmospheric conditions (net solar radiation, temperature, humidity, etc.) affect transpiration and hence the rate of root water uptake. To formulate a comprehensive equation for calculating this rate, interaction between the above features has been taken into account.

2. In this study a mathematical model for predicting the rate of tree root water uptake was developed. Equation (3.16) represents the proposed formula, which considers three independent features, soil suction, root distribution, and potential transpiration.

9.2.2 Numerical modelling of the interaction between tree and ground

1. The model developed for the rate of root water uptake was included in a numerical analysis using the ABAQUS finite element code to examine the distribution of suction and a profile of the moisture content close to trees.

2. The numerical model takes into account the coupled flow-deformation equations. Finite element discretisation was formulated using partially saturated elements capable of capturing the role of unsaturated permeability and degree of saturation at various levels of matric suction. Root suction was part of the analyses through the model developed in this study, which also included the soil matric suction and distribution of root density, potential transpiration, and root growth rate. Figure 9.1 shows a summary flowchart of the recommended predictive procedure for the influence of tree roots on the ground.

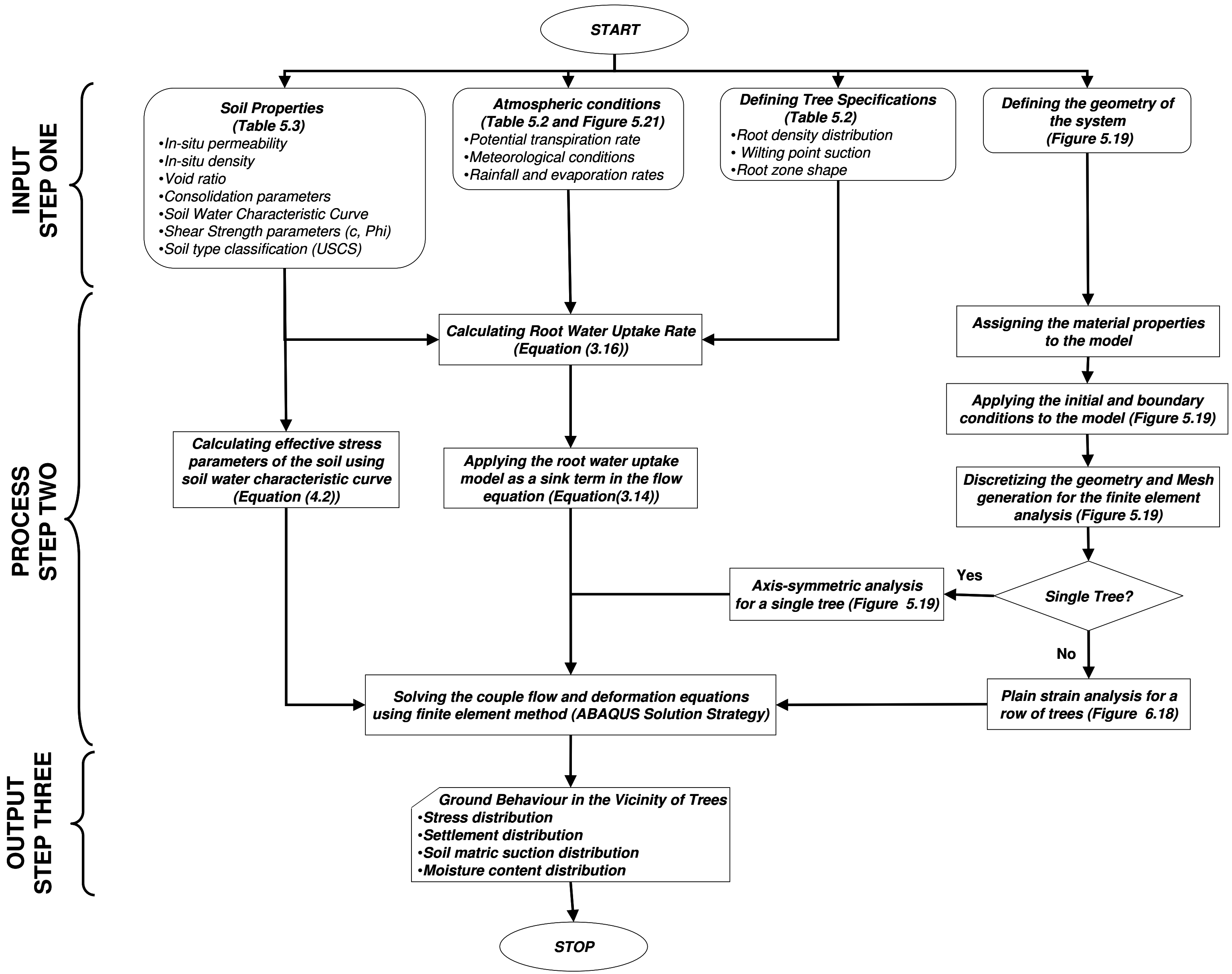

Figure 9.1 Flowchart of the predictive procedure of the proposed model

9.2.3 Field and laboratory programs

1. A profile of the moisture content and suction around a Eucalyptus largiflorens tree in western Victoria, Australia, was determined by taking disturbed and undisturbed samples of moisture content and soil suction.

2. The properties of soil, including the physical and mechanical parameters, the specifications of a tree and its atmospheric conditions near a Eucalyptus largiflorens tree were measured for use in a validation exercise.

3. The distribution of the roots of this tree seen through trenches excavated in different directions, showed that they developed 20m horizontally and 3m vertically.

4. Field observations showed a moisture deficit close to the Eucalyptus largiflorens tree extends approximately 20-25 m away from the trunk.

5. Laboratory experiments to measure physical and mechanical parameters of soil were carried out. The key experiments were soil water characteristic curve using a pressure plate and filter paper, hydraulic conductivity using double-ring permeameter, consolidation, triaxial, and organic content. All the required model parameters were measured, as reported in Chapter 5.

9.2.4 Case history analysis

1. The validity of the numerical results was successfully examined by comparing the ABAQUS output with a similar analysis performed by Fredlund and Hung (2001).

2. The results of a numerical prediction of the matric suction and moisture around a single Black Box tree located in western Victoria, Australia, were compared with field data taken in May 2005 and April 2006. A good agreement was generally obtained between the measured and simulated distribution of soil moisture. It was also shown that a numerical analysis that includes the proposed root water uptake model could reasonably predict the region of maximum matric suction 8.5m away from the axis of the trunk, as measured in the field. Ground displacement contours

for this case study indicated that the maximum settlement after about 3 years occurred on the surface, 6m away from the trunk.

3. In the first verification case study, the results of the predicted soil matric suction around a single Eucalyptus tree were compared with various field data reported by Jaksa et al. (2002). A comparison between predicted results and measured soil suction indicated similar trends. It was also shown that a numerical analysis incorporating the proposed model could reasonably predict the point of maximum suction change away from the axis of tree, as measured by Jaksa et al. (2002).

4. The settlement contours for the first case study indicated that the maximum settlement at the initial stages (less than one month) occurred near the point with the highest root water uptake rate, but below the trunk over a longer term (after 12 months).

5. In the second case study, the results of the predicted reduction in moisture around a single lime tree were compared with field data reported by Biddle (1983). There were some uncertainties in the assumed soil parameters, actual tree root distribution, and atmospheric parameters, but there was fundamental agreement between the measured and simulated distribution of moisture.

6. In the third case study, an evaluation of the model developed in this study was successfully carried out by comparing the numerical results and field measurements of the moisture content near *a row of Poplar trees*, as reported by Biddle (1998). Despite uncertainties in an assumption of the actual distribution of tree roots, atmospheric parameters (e.g. potential transpiration), and soil parameters (e.g. hydraulic conductivity, soil water characteristic curve and consolidation parameters), there was an acceptable agreement between the measurements and predicted distribution of moisture.

7. As transpiration and soil consolidation are time dependent functions, the influence of elapsed time was investigated by conducting a transient ground analysis. The results indicated that the matric suction and vertical deformation increase over time, being more important when transpiration begins.

8. The results of this study provide a valuable and a relatively accurate means of estimating how vegetation affects the ground. The numerical model developed

herein offers practicing geotechnical engineers a powerful tool for designing structures on a vadose zone with native vegetation.

9.2.5 Parametric study and sensitivity analysis

1. An array of numerical analyses based on the theory of water flow in partially saturated soils, including the model for root water uptake, was conducted. The results show that an increased rate of potential transpiration causes a greater change in matric suction and ground settlement. Moreover, when the maximum root length density increases, surface settlement increases and the point of maximum settlement moves toward the axis of the tree. In addition, the maximum soil matric suction decreases with the value of saturation permeability (k_s), but its rate increases at higher values of k_s.

2. The findings of a sensitivity analysis confirmed that a number of parameters should be accurately measured or estimated for a properly designed foundation. Soil permeability, wilting point suction, density and distribution of the root length, and the rate of potential transpiration have a significant effect on the ground. The sensitivity indices presented here were related to the nominal operating values, which were the initial conditions used in the analysis. It was also shown that for different ranges of operating values, sensitivities associated with the same variable changed slightly.

3. The two sensitivity analyses previously conducted for trees with relatively shallow and deep root zones, showed that the settlement results are quite sensitive to soil permeability in the range of 5×10^{-7} to 10^{-8} m/s, potential transpiration greater than 45 l/day, a coefficient of vertical root distribution greater than 5 m^{-1}, and a wilting point suction larger than 1500 kPa.

4. The results of the parametric study have also shown that some of the parameters (e.g. k_4, a coefficient related to the effect of depth on potential transpiration) do not affect the ground very much, but these results are related to the initial values and assigned range of parameters implemented in the reference case. In some real cases, the results may vary and change the sensitivity indices of the parameters.

9.3 RECOMMENDATIONS FOR FUTURE WORK

Further analytical, numerical and experimental studies associated with the interaction between tree, ground and atmosphere are recommended. Future research work may be carried out in the following areas:

1. Further field measurements near Australian native trees to determine the root distribution and the way different species remove water from the ground. Further research at an 'instrumented site' to continuously record the moisture content and suction would be desirable because this may provide further insight into the effect of transpiration and other hydrological features.

2. A series of large scale laboratory tests to assess the heterogenous and anisotropic properties of soils mixed with roots. Active tree roots can influence basic soil properties including hydraulic conductivity, the soil-water characteristic curve, compressibility, and shear parameters. Further study on how the content of different roots on the properties of soil can enhance modelling the interaction between vegetation and ground.

3. Extend the model to include the root zone as natural reinforced earth, whilst including the enhanced shear strength and stiffness parameters. Minute tree roots may increase the apparent cohesion of the soil matrix, while larger roots tend to act as individual anchors.

4. Extend the model to include the surface topography, redistribution of rainfall and evaporation due to the size of the tree canopy, as well as osmotic suction induced by different salt concentrations in the soil. For this purpose, all the details, measurements, and specifications pertaining to these parameters are required. And finally, the osmotic driving force needs to be incorporated in the coupled flow and deformation equations.

5. Apply the proposed model to slope stability problems and evaluate the results against performance in the field. This would require a new set of ground geometry data, tree root properties, meteorological data, and geotechnical site investigation data for naturally reinforced slopes. The appropriate effect of induced matric suction by transpiration would need to be introduced into an analysis of slope stability, which should result in higher safety factors.