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

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CHAPTER ONE

1 INTRODUCTION

1.1 GENERAL

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, intrastate, and interstate networks covering all states and territories, totalling 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. The process of extensive ballast maintenance following heavy rains is both costly and highly drawn out. For example, it has been reported that the cost of maintaining Sydney's rail network exceeded two billion dollars in the last decade. Due to the high maintenance costs involved, the importance of finding appropriate cost minimisation methods can therefore be clearly perceived. Bioengineering aspects of native vegetation are currently being used to improve the soil stiffness, stabilise slopes and control 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 helps stabilise the tracks near the root zone. Figure 1.1 illustrates schematically the effect that a single tree near a railway track has on the ground in the immediate vicinity.

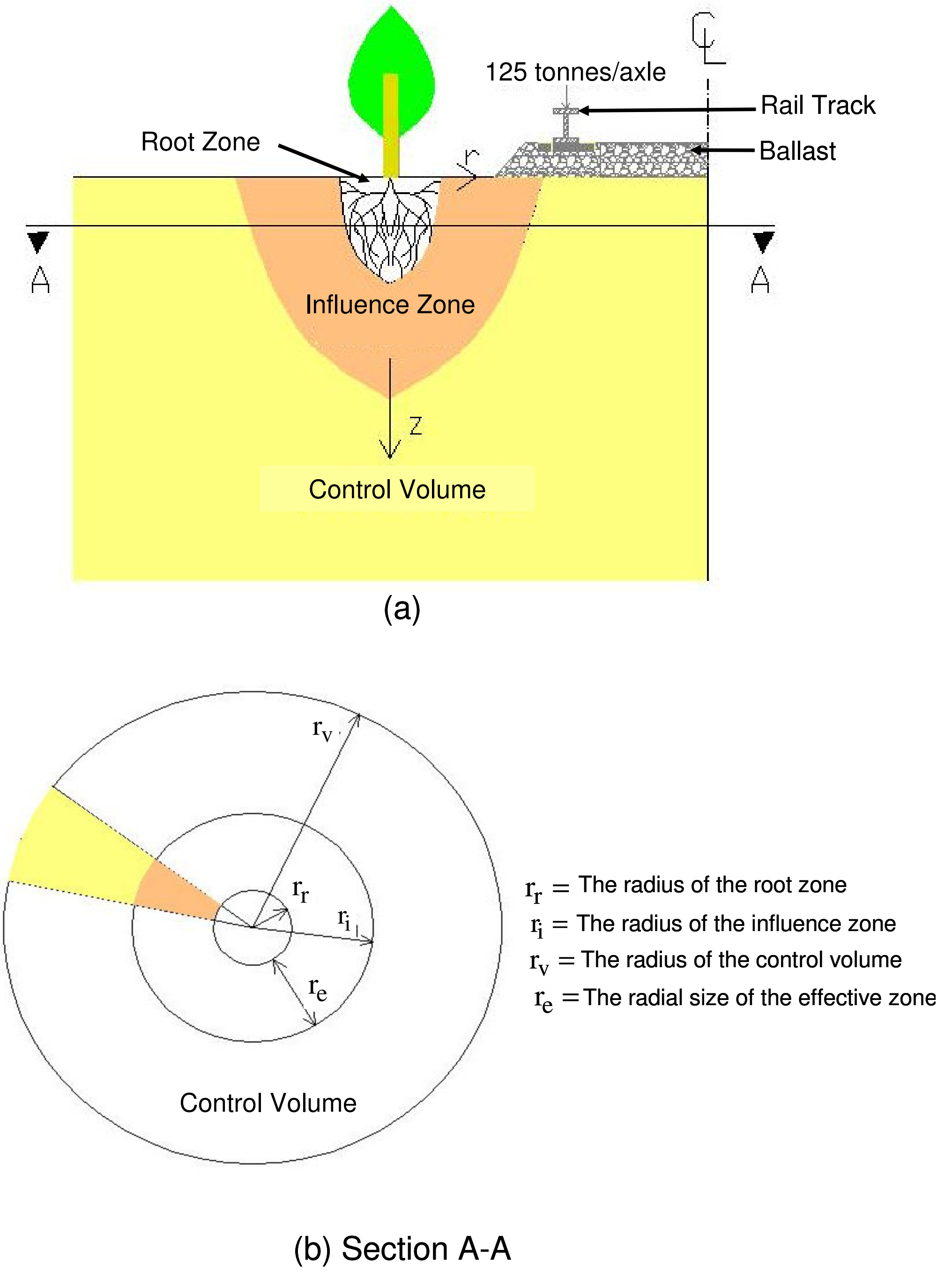

Figure 1.1 (a) Two dimensional vertical view of the root zone and the influence zone of a tree (b) a schematic horizontal cross section

1.2 DESCRIPTION OF PROBLEM

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.

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. This is because, ballast pocket is one of the problems they face. Because of heavy trains or ballast tamping to reshape and level the ballast, a ballast bowl (or ballast pocket) in which water sits and softens the ground can be formed in the base region. This region is the foundation of the rail track and is critical in determining how it will perform under load. Although maintenance programs pay more attention to drainage, it is often unsuccessful in itself due to site restrictions such as limiting topography. As there is a lack of knowledge of the interaction between vegetation and ground, complete and appropriate design procedures for strategically planted vegetation is still unavailable. In fact, the soil moisture profile close to vegetation, the influencing factors, the zone influenced by vegetation and its properties are not clearly established for design purposes.

1.3 APPLICATION OF NATIVE VEGETATION FOR GROUND MODIFICATION

There are several engineering solutions (i.e. inert systems) in common use for soil stabilisation on non-sloping ground, such as the inclusion of geosynthetics and using chemical agents (cement, lime, lignin, etc) to stabilise soft soils and certain expansive soils (Kitsugi, 1989; Chmeisse, 1992; Indraratna, 1996). Accelerating the rate of consolidation of soft soils using vertical drains together with pre-loading, is another technique to improve the condition of soft soil (Kjellman, 1948; Indraratna et al. 2000). However, these engineering solutions are usually more expensive than native vegetation based stabilisation.

Trees can provide suction up to the wilting point of a soil-root system (approximately 3 MPa) and therefore, ground consolidation associated with transpiration increases the strength and stiffness of the soil. This process may be compared with improving soft soil via pre-fabricated vertical drains and vacuum pre-loading. In fact, transpiration is similar to a vacuum in that it results in an increase in the hydraulic gradient and effective stress in soil which leads to consolidation without positively increasing the initial excess pore pressure. Although transpiration depends on the size of the root zone, which can be shallow or deep depending on the type of vegetation and condition of the soil, the root-based suction (negative pore water pressure) is much greater (>10 times) than that, which is practical as a vacuum for a pre-fabricated vertical drain system. The suction induced by transpiration increases the effective stresses, which in turn increases the settlement and stiffness of unsaturated soil.

Nevertheless, geotechnical engineers have been reluctant to adopt vegetation-based stabilisation. This is partly due to the perception that vegetation is unpredictable, which results in the possibility of non-uniform patterns of soil moisture reduction. Another reason is time dependency; it is often assumed that a five to ten year delay is required for the roots to strengthen and dry the soil.

1.4 OBJECTIVES AND SCOPE OF STUDY

The main objective of this study is to develop an integrated transient model that considers the extraction of soil water by roots within the vadose zone to simulate ground covered by vegetation. The research work consists of three parts, (a) development of a new root water uptake model and numerical analysis of the interaction between vegetation and soil, (b) conducting field measurements and using laboratory experiment, and (c) validation of the model using field and laboratory data, and sensitivity analysis.

The specific objectives of the model development component of this study are as follows:

- Finding the independent factors that influence the rate of root water uptake and the need for developing a rigorous model.

- Developing a mathematical model for the rate of root water uptake that includes soil conditions, type of vegetation, and atmospheric conditions.
- Incorporating the root water uptake model in the coupled flow and deformation equations.
- Identifying all coefficients involved in the governing equations in terms of measurable physical parameters.
- Implementing the developed model for the rate of root water uptake in a numerical analysis using a finite element method to examine the distribution of soil suction and profile of the moisture content close to vegetation.

The main objectives of the field measurements and laboratory experiments are:

- A geotechnical field investigation to observe the influence of a representative single tree on the ground and the way in which vegetation discharges moisture from the surrounding area.
- Collecting disturbed and undisturbed soil samples near a tree on a selected site to measure its properties.
- Constructing a soil-water characteristic curve (the degree of saturation versus matric suction) at different depths.
- Determining the soil moisture content and suction profile around the tree by obtaining disturbed samples and undisturbed samples.
- Observing and determining the distribution of roots of a selected tree for specific site conditions.
- Collecting field data to predict the zone of influence of the tree
- Measuring the parameters of the soil, tree and atmosphere for numerical modelling and validation exercise.

The key objectives of a validation exercise based on field and laboratory data, and sensitivity analysis are:

- Examining the validity of the numerical predictions by comparing the finite element outputs with the field and laboratory results previously obtained.
- Verifying the proposed model using a simulation of some results previously published in this area.
- Studying the effect of changing the soil, tree, and atmospheric parameters on the numerical predictions.
- Determining the key parameters that significantly influence ground conditions in close to vegetation.
- Offering practicing geotechnical engineers an effective tool for designing structures on a vadose zone under the influence of native vegetation.

1.5 ORGANISATION OF THE THESIS

Following this introduction, Chapter 2 presents a comprehensive survey of literature associated with the interaction between vegetation and ground. The hydrogeological features influencing the ground, key parameters controlling the rate of root water uptake, methods for measuring soil suction, previously published literature containing the field investigations of the interaction between tree and ground, and a detailed review of predictive mathematical and numerical models are presented.

Chapter 3 presents the development of a root water uptake model for soil properties, specifications for vegetation, and meteorological conditions. The model developed here incorporates key factors such as soil suction, active root density distribution and potential transpiration. The influence of various factors such as changing of the root density distribution and wilting point suction and any variation to potential transpiration and its distribution are discussed. Although in this study a numerical solution has been used to solve the nonlinear coupled flow and deformation equations for partially saturated soil under transpiration, an analytical solution for a simplified case with constant root water uptake model has also been presented.

Chapter 4 is devoted to the theoretical development of the problem of obtaining governing equations for coupled flow and deformation of unsaturated soil with consideration to the root water uptake model. In addition, the solution to the finite element procedures of the proposed mathematical formulations are presented and discussed.

Chapter 5 describes the detailed field investigation conducted near a Eucalyptus largiflorens tree, which is an Australian native. These field investigations included field procedures such as drilling boreholes and taking soil samples, measuring the soil moisture content and suction, conducting cone penetration tests and excavating trenches to observe the distribution of tree roots under the ground. To verify the model, the soil moisture content and suction profiles were compared to the predicted values. Furthermore, profiles of ground settlement adjacent to the tree are presented and interpreted.

Chapter 6 explains the application of the proposed model to four case studies relating to the field measurements of soil suction and moisture content near a single Eucalyptus tree in Adelaide, Australia, as reported by Jaksa et al. (2002), a single lime tree in Milton Keynes, U.K, as reported by Biddle (1983), and a row of Poplar trees in Cambridge, U.K, as reported by Biddle (1998). Furthermore, the validity of the numerical results has been examined by comparing the numerical outputs with a similar analysis performed by Fredlund and Hung (2001).

Chapter 7 illustrates the results of a sensitivity analysis using the finite element method to study the influence of some parameters on ground behaviour. The rate of selected parameters such as potential transpiration and its distribution, suction at wilting point, the coefficient of permeability, and distribution of root length density are studied in detail. The analytical results in the form of changes to the soil matric suction and settlement for different key parameters are presented and discussed.

Chapter 8 describes the practical applications of native vegetation for soft ground improvement. The action of a single tree on improving the soil behaviour is compared to a vertical drain with applied suction (vacuum pressure) in the vicinity of railway lines.

Chapter 9 presents the conclusions of the current research and recommendations for further research, followed by the Bibliography and Appendices.