Soil Stabilisation Using Native Vegetation

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ABSTRACT: Civil engineering is in the challenging situation of trying to discover cost effective, reliable, and sustainable methods for ground improvement to meet the current demands needed for infrastructure facilities. The concepts of green corridors or vegetation induced ground improvement are more effective techniques than other ground improvement methods because trees increase the matric suction of the soil subgrade beneath the substructure via root water uptake in conjunction with the evapo-transpiration of their canopy. Moreover, the root network of trees provides a significant mechanical reinforcement as well as an additional cohesive increment as their hair roots generate osmotic suction. This paper presents the requirement of an advanced shear strength model that captures and combines the effect of root reinforcement with osmotic and matric suction components generated in the soil via the naturally coupled osmotic evapo-transpiration phenomenon.

1 INTRODUCTION

The concept of a green corridor is an expedient method for most geotechnical engineering projects provided its subsequent effects have been thoroughly quantified, because in this concept, tree roots are the most important parts.

The root system of a tree can be broadly categorised into two sub root systems known as the active root system and the main root system. Small (active) roots contribute to the uptake of water and nutrients while main roots help to stabilise the tree. These two root systems provide mechanical strengthening to the soil by means of anchoring and increments of cohesion (Fatahi, 2007). Moreover, tree roots also improve the matric suction of soil by means of the root water uptake in conjunction with the evapo- transpiration of the tree (Fatahi, 2007). This means the true effect of vegetation on the stability of soil consists of mechanical strengthening and suction improvement, including the influence of suction on mechanical strengthening.

A mature tree can develop 30Mpa of root suction at wilting point during evapo-transpiration (Fatahi; 2007). This leads to the soil becoming desiccated, which in turn increases and preserves the vadose zone. Quantifying the mechanical strengthening parameters was usually done for saturated soils, with most being based on empiricism (Docker, 2008; Docker, 2009).

Even though native vegetation is still not commonly used as a ground improvement technique, field studies have already shown its potential for stabilising slopes and controlling erosion. For instance, Potter (2006) conducted extensive field studies to evaluate the true effect of vegetation and the associated development of matric suction underneath the railway lines in Miram, Horsham, and WalWal in Australia. He reported that the variations in total suction underneath a railway track in non-vegetated and vegetated conditions were distinct, with the latter typically exhibiting larger values of suction.

In ground improvement, it is therefore important to understand the root system of trees despite already knowing about strengthening via the development of suction or mechanical strengthening. According to the Indraratna et al. (2014), the total generation of shear strength in terms of mechanical strengthening and suction induced by root water uptake, is mainly governed by the spatial distribution of the root system. Therefore, a comprehensive understanding of the root system is vital for an in depth study of the effect of suction on soil stabilisation.

The spatial distribution of root systems varies according to environmental factors such as species, soil conditions, temperature, wind speed, and humidity. However, bioengineering techniques can be used in hill slopes where there are risks of landslides, as well as for other improvement processes (Bache et al. 1989; Docker and Hubble, 2001; Potter, 2006; Fatahi, 2007)

2 SUCTION EFFECT

The root water uptake of a tree increases the matric suction of the adjacent soil due to the subsequent reduction in the moisture content. This can be very significant because trees such as Pinus radiata can absorb amounts of water equal to its own weight per day, and most mature trees can generate up to

30MPa of suction in their soil-root systems. The main factor that affects the root water uptake is the rate of transpiration of a tree because the volume of water consumed by plant cells for metabolism is negligible compared to the total root water uptake (Radcliffe et al., 1980)

2.1 *Rate of root water uptake and transpiration*

Only active roots uptake water through the process of osmosis, but the rate of uptake in a given time varies from point to point in a root system according to the spatial distribution of the active roots. The rate of root water uptake has been described considering the hydraulic conductivity of leaves and water potential differences between root and soil (e.g.Gardner, 1960; Whisler et al., 1968; Molz and Remson, 1970; Feddes et al., 1974; Hillel et al., 1976). Furthermore, recently Fatahi (2007) developed a more comprehensive approach to evaluate the rate of root water uptake considering transpiration of tree canopy (Eq. 1).

$$S(x,y,z,t) = f(\psi)G(\beta)F(T_P) \qquad (1)$$

where, $F(T_P)$ is a factor related to the potential transpiration model developed by Nimah and Hanks (1973) which can be described according to Eq. 2.

$$F(T_p) = \frac{T_p(1 + k_4 z_{max} + k_4 z)}{\int_{v(t)} G(\beta)(1 + k_4 z_{max} + k_4 z)\,dv} \qquad (2)$$

where $G(\beta)$ is the root density which depends directly on species of tree and condition of the soil, and k_4 is an experimental coefficient (Fatahi et al., 2010). The coefficient k_4 depends on the rate of transpiration, which is directly affected by the environmental factors such as the humidity, temperature, and wind speed, as well as soil moisture (soil water potential) and physiology of the tree, and $f(\psi)$ is the factor related to the soil moisture condition. The soil water potential inversely affects the root water uptake, while the soil suction relates to the soil moisture content through the soil water characteristic curve. Therefore, the soil reduction factor is a function of the moisture content of soil (Indraratna et al., 2008; Fatahi et al., 2009).

The flow equation related to the unsaturated soil incorporating the root water uptake as a sink term is as follows;

$$\frac{\partial\theta}{\partial t} = \nabla.(k\nabla\psi) - \frac{\partial k}{\partial z} - S(x,y,z,t) \qquad (3)$$

3 MECHANICAL STRENGTHENING

The effect of root reinforcement with regards to the bioengineering aspects of controlling slope stabilisation and erosion has been widely discussed over the past few decades. Waldron (1977) and wu et al. (1979) developed a simple root model for vertical root, and then Gray and Leiser (1982) modified the model for an inclined root.

Waldron (1977) defined three different increments of shear strength (ΔS) related to the three different failure patterns known as stretching, slipping, and breaking. According to Waldron (1981), an increment of the shear strength (ΔS) can be added directly to the coulomb equation because there is no change in the friction.

$$\tau = c + \Delta S + \sigma_N \tan\phi \qquad (4)$$

Docker and Hublle (2009) carried out many in-situ direct shear tests of root permeated saturated soil for four Australian tree species, and then introduced an emperical equation (Eq. 5) for the shear strength increments that were mainly based on the Root Area Ratio (RAR)

$$\Delta S = B.(RAR) + C \qquad (5)$$

$$\text{Root Area Ratio (RAR)} = \frac{\text{Area of Root Along the Shear Plane}}{\text{Area of the shear Plane}}$$

In Eq. 5, 'C' and 'B' are experimental coefficients related to the different tree species.

4 DISCUSSION

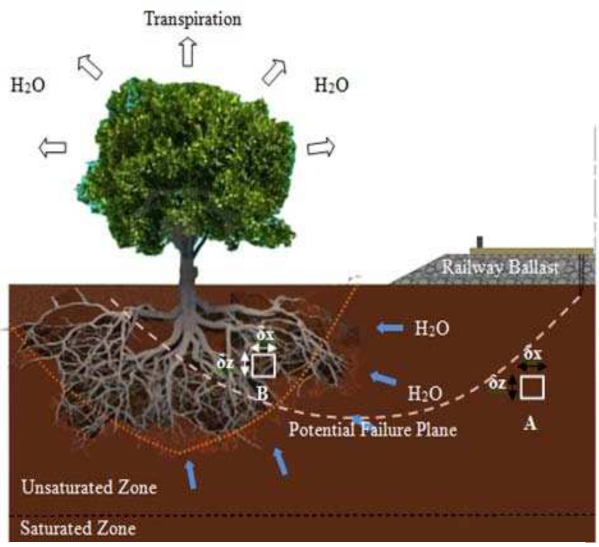

Fig 1. Schematic diagram of root water uptake process and root reinforcement.

As stated in the introduction, most sub soil structures remain in a partially saturated state where it is certain that the depth and degree of saturation of the vadose zone increases in that part of the soil structure which interacts with mature trees. As a result, the parameters developed for mechanical strengthening in a saturated condition are not realistic, and therefore a combined effect must be included, and the parameters should be defined accordingly.

Fig. 1 gives a general understanding of an improvement in the subsoil structure due to this combined effect. Soil element A in Fig.1 is directly under the Railway ballast and Soil element B is in the area of the root zone. General unsaturated soil mechanics theories are valid for soil element A and therefore Vanapalli, Fredlund et al. 1996 equation can be used

$$\tau = c' + (\sigma_n - u_a)tan\phi' + (u_a - u_w)\left[tan\phi'\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)\right] \quad (6)$$

In this equation u_a and u_w are the pore air and water pressures, θ_s, θ_r, and θ are the saturated, residual, and instant volumetric water contents, and all the other symbols have their usual meaning.
The value of θ in this equation changes with time due to the root water uptake, so the following equation can be stated by considering Fatahi's 2007 equation and Reynolds differential transport theorem.

$$\frac{\partial\theta}{\partial t} = \nabla.(k\nabla\psi) - \theta\frac{\partial k}{\partial z} - dS(x, y, z, t) + dI(x, y, z, t) \quad (7)$$

In this equation 'S' is the Root water uptake sink term and 'I' is the irrigation source term, θ is the volumetric moisture content, k is the hydraulic conductivity, and ψ is the matric suction. At the same time the usual soil water characteristic curve can be used for element 'A'.

Element 'B' has a significant effect from the root suction and root reinforcement because it is in the root zone of the tree, and therefore the usual unsaturated soil mechanics theories cannot be directly used for element 'B'. However, the stiffness of the root zone increases the shear strength of the soil around element A, so it can be defined as a "shear capacity" of the root area zone which acts as an external stiffener with help from the root reinforcement and suction.

Fig. 2(a) shows a schematic diagram of the root zone and water uptake points. According to the enlarged view of the root tip shown in Fig. 2(b), and according to the classical botanical understanding, osmosis at the root tip binds the soil matrix together, and therefore the failure patterns described in Section 3 may be altered such that it is governed

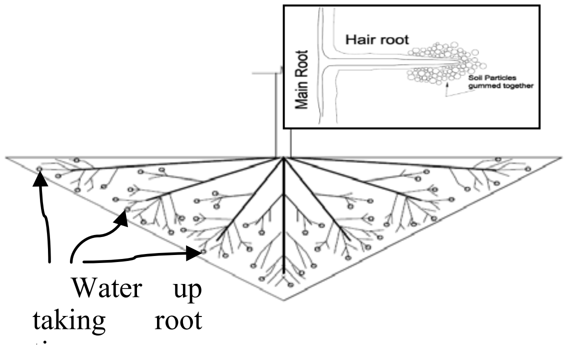

Fig. 2 (a) Schematic diagram of root system with distribution of water up-taking active root tips, (b) Enlarged root tip.

by osmosis at the root tip. The suction changes the bond strength between the root and the soil, and also alters the material properties of the root. In this case the failure of the root system due to slipping, stretching, breaking, or pulling out with the soil annulus were greatly affected by suction induced by the tree roots, as well as the adjacent soil suction.

Computing the effects from root reinforcement and suction separately and then superimposing them may not give a realistic answer because the suction influences the root reinforcement. Suction changes the bond strength between the root and the soil and also alters the material properties of the root. In this case the failure of the root system due to slipping, stretching, breaking, or pulling out with soil annulus were greatly affected by suction induced by the tree roots, as well as the adjacent soil suction.

5 CONCLUSIONS

Tree roots can be used economically to improve the subgrade after the subsequent affects have been analysed. Previous models that were developed to compute the root based suction and root reinforcement effect have contributed to improvements in the sub grade, but as described in this paper, a comprehensive model consisting of mechanical strengthening and root based suction is needed to obtain more realistic results. Moreover, most trees are unable to improve the sub soil because of their shallow root system and deciduous behaviour. Therefore it is essential to select plants with a good root system and which are evergreen.

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