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Improvement of soil stability along rail corridors through native vegetation

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Improvement of soil stability along rail corridors through native vegetation

Abstract

Field studies conducted along the railway lines in Australia have revealed the ability to implement the green corridor concept as a soil stabilization method. Native trees grown along rail corridors are capable of increasing the matric suction of the subgrade soil underneath the track substructure via root water uptake, in conjunction with the tree canopy evapo-transpiration. Moreover, these trees are capable of providing significant mechanical reinforcement through the anchoring effect provided by the root network plus the additional cohesive increment due to hair roots generating osmotic suction. Much of the previous research carried out to quantify the mechanical strength generated by tree roots has been mainly based on empiricism. In many cases, empirical relations have been developed for a given tree species grown under known soil conditions. The extrapolation of such empirical relations from one tree-soil system to another can be misleading. Furthermore, the effect of transpiration by tree canopy and its influence on the sustained suction equilibrium generated at the root zone for stabilising soft subgrade has not been considered rationally. To accommodate the above natural phenomena, a novel computational model has been developed to quantify the overall suction effect provided by the tree roots and its continual link with the rate and magnitude of canopy evapo-transpiration. Root based suction of a tree improves the shear strength; accelerates the pore water pressure dissipation and it may alter the potential failure conditions of the soil-root system from a saturated to an unsaturated domain. Therefore, it is necessary for the root based suction and the mechanical properties of the root network to be analysed within a coupled multiphase framework. Accordingly, this paper will present the requirement of an advanced shear strength model that captures and combines the root reinforcement effect with both osmotic and matric suction components generated in the soil through naturally coupled osmotic evapo-transpiration phenomenon.

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Improvement of Soil Stability along Rail Corridors through Native Vegetation

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ABSTRACT

Field studies conducted along the railway lines in Australia have revealed the ability to implement the green corridor concept as a soil stabilization method. Native trees grown along rail corridors are capable of increasing the matric suction of the subgrade soil underneath the track substructure via root water uptake, in conjunction with the tree canopy evapo-transpiration. Moreover, these trees are capable of providing significant mechanical reinforcement through the anchoring effect provided by the root network plus the additional cohesive increment due to hair roots generating osmotic suction. Much of the previous research carried out to quantify the mechanical strength generated by tree roots has been mainly based on empiricism. In many cases, empirical relations have been developed for a given tree species grown under known soil conditions. The extrapolation of such empirical relations from one tree-soil system to another can be misleading. Furthermore, the effect of transpiration by tree canopy and its influence on the sustained suction equilibrium generated at the root zone for stabilising soft subgrade has not been considered rationally. To accommodate the above natural phenomena, a novel computational model has been developed to quantify the overall suction effect provided by the tree roots and its continual link with the rate and magnitude of canopy evapo-transpiration. Root based suction of a tree improves the shear strength; accelerates the pore water pressure dissipation and it may alter the potential failure conditions of the soil-root system from a saturated to an unsaturated domain. Therefore, it is necessary for the root based suction and the mechanical properties of the root network to be analysed within a coupled multiphase framework. Accordingly, this paper will present the requirement of an advanced shear strength model that captures and combines the root reinforcement effect with both osmotic and matric suction components generated in the soil through naturally coupled osmotic evapo-transpiration phenomenon.

Keywords: soil suction, mechanical strength, shear strength, transpiration

1 INTRODUCTION

Green corridor concept in soil stabilisation can be considered as an environmental friendly, economic and expedient method which has been proven the usability by various field studies. When the native vegetation is to be used as a ground improvement method, thorough engineering quantification of its subsequent effects should be carried out. Tree roots are the most important parameter of the soil stabilaisation process using native vegetation, and the complexity of the root architecture may lead to unpredictable results if it is not well studied.

Tree roots increase the soil suction during the process of root water uptake in conjunction with evapo-transpiration process (Fatahi et al. 2009). Moreover, tree roots similar to geo fibres provide the mechanical strengthening to the soil matrix by increasing cohesion due to small flexible roots as well as by the anchoring effect due to large stiff roots (Fatahi 2007; Docker and Hubble 2001). Therefore, to determine the true effect of the vegetation on shear strength of the soil, the mechanical strengthening associated with the variation of suction induced by tree roots (i.e. hydraulic processes) as well as the influence of the suction on root reinforcement (i.e. physical reinforcement) have to be taken into account.

Even though the native vegetation is still not very commonly used as a ground improvement method, there have been field studies which demonstrated its potential use for slope stabilisation and erosion control. For instance, Potter (2006) conducted extensive field studies to evaluate the true effect of vegetation and associated matric suction development underneath the railway lines in Miram, Horsham and Wal Wal in Australia. It was reported that the total suction variation underneath a railway track for a non-vegetated and vegetated condition are distinct and that the latter typically exhibits larger values of suction.

Furthermore, previous research conducted to quantify the effect of mechanical strengthening of tree roots in slope stabilisation have been mainly focused on saturated soil conditions supported by empirical relationships (e.g. Docker and Hubble 2001; Docker and Hubble 2008). In contrast, Fatahi et al. (2009) showed that when a mature tree is under the evapo-transpiration process, tree roots are capable of developing 3MPa root suction at wilting point and this leads to the enhancement and preservation of the vadose zone. Therefore, the sub-soil structure is often under unsaturated condition and the parameters calculated for the saturated condition may not truly represent field conditions. In that case the quantification of the suction generated on soil adjacent to tree roots is important.

Tree physiology, soil condition and other environmental parameters such as temperature, wind speed and humidity affect the suction development in soil by trees (Fatahi et al. 2014). Among these, the parameter that governs the suction development as well as the mechanical strengthening of soil is the spatial distribution of root systems. This is because the distribution of the hair roots (active) in the root system controls the soil suction variation and the distribution of main roots controls the amount of root reinforcement generated. The amount of shear strength generated by means of suction as well as the root reinforcement is accountable by the spatial distribution of root system, which in turn varies according to the environmental factors even among the same tree species. However, it has been proven that the bioengineering techniques can be effectively 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)

1.1 Spatial distribution of a root system

Absorption of water, minerals and nutrients, synthesis of various essential compounds such as growth regulators, storage of food in root crops and anchoring tree to the ground are the main functions of roots. Therefore, the spatial distribution of a root system shows inhabitant behaviours according to the availability and requirement of above parameters. Quantitative understanding of the root system is important since its shape directly affects the shear strength improvement of soil. In addition, different tree species have distinct root systems and properties of the soil also affect the depth and the spatial distribution of the root system. Two main root systems can be distinguished in trees are the fibrous root system and the tap root system. Typically, in well-drained soil conditions roots mainly have a fibrous root system and often results from a combination of lateral and oblique roots with no real tap root. In fact, only a small percentage of tree root systems have a real tap root. (Kramer 1995)

1.2 Environmental factors affecting the root growth

The environmental factors which affect the growth of tree roots are soil texture and structure; aeration; moisture; temperature; pH; salinity; the presence of toxic elements such as lead, copper, aluminium; competition with other plants and presence of bacteria, fungi and soil inhabiting animals (Weaver 1958). Common variations in shapes of root systems influenced by environmental factors such as soil bulk density, temperature and rainfall amount are illustrated in Figures 1 and 2.

Trees grown in different areas with different environmental factors display severe changes in their root systems, despite the above fact, root based suction applying on adjacent soil by a mature tree, is approximately 10 times greater than the practical vacuum for a prefabricated vertical drain (Indraratna et al. 2008). Therefore, this paper aims to present the model developed to capture the root based suction in conjunction with evapotranspiration and the importance of the combined effect of root reinforcement and suction.

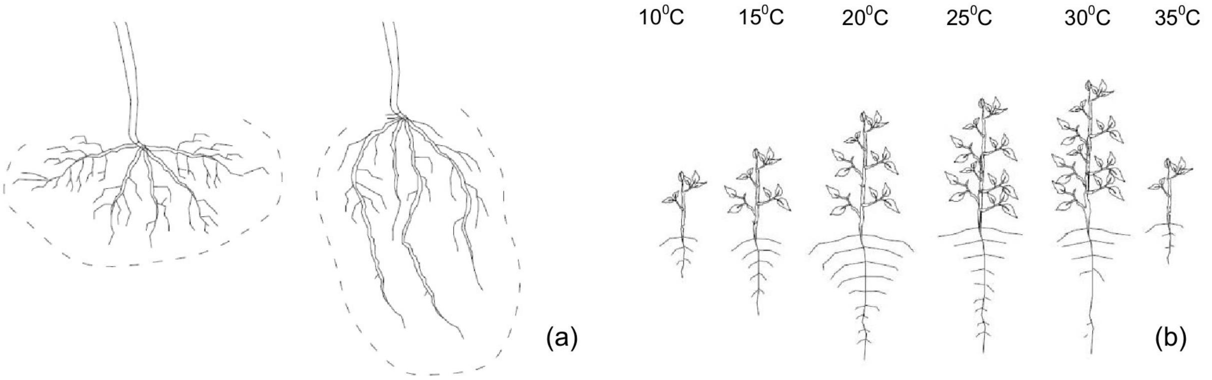


Figure 1 (a) Root system of young barley plants grown in the field in soils with different bulk densities (Left) 1.35 g cm $^{-3}$*; (right) 1.50 g cm* $^{-3}$*(Gilmen1980) (b)Influence of root zone temperature on root morphology and shoot growth of potato seedlings (modified after Sattelmacher et al. 1990)*

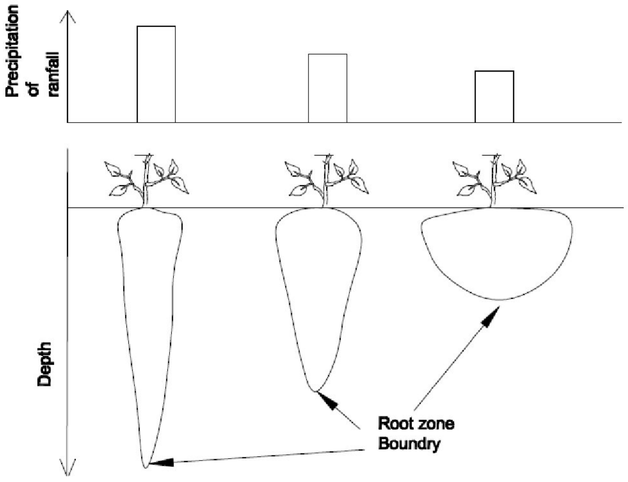


Figure 2 Schematic diagram of the effect of the amount of rainfall on the depth of rooting of winter wheat (very fine sandy loam - silty loam in the Great Plains) (modified after Sattelmacher et al. 1990)

2 SUCTION EFFECT OF TREE ROOTS ON SOIL

The root water uptake of a tree increases the matric suction of the adjacent soil due to reduction of the moisture content. This can be very significant as some tree varieties like *Pinus radiata* can absorb water amounts up to its own weight per day and most mature trees can generate suction in soil-root systems up to 30MPa. The main factor that affects the root water uptake is the rate of transpiration of a tree, since 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

Root water uptake takes place only by active roots of the tree through an osmotic process. The rate of root water uptake in a given time varies from a 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.

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

where, G(β) is the root density effect which directly depends on tree species and soil condition and $k_4$is an experimental coefficient (Fatahi et al. 2010). The coefficient k_4 depends on the rate of transpiration which is affected by the environmental factors, e.g. humidity, temperature, wind speed as well as soil moisture condition (soil water potential) and tree physiology. The effect of humidity, which is the amount of water vapour in the air, can be computed using Fick's law of diffusion for the rate of transpiration and it is assumed as directly proportional to the difference in vapour pressure between leaf and the atmosphere and inversely proportional to the summation of resistance to water flow encountered in air (Fatahi 2007). Temperature regulates the transpiration to high extend through its effect on vapour pressure, if there is no any inhabitant acclimatization in the plant species. In example, a leaf exposed to full sunlight may experience temperatures reaching 50^0C to 100^0C. If the leaf stomata remains open, transpiration will occur and vapour will condense once it emerges from the leaf. This phenomenon is called "steaming jungle" and occurs in tropical jungles (Hopkins (1999). Wind speed controls the transpiration through the change of resistance and effective length of diffusion path of water vapour (Nobel 1991). For higher wind speeds, the rate of transpiration increases due to the depletion of diffusion path. Even though the transpiration of tree leaves are affected by wind speed it is also subjected to the inhabitant acclimatization of the plant species.

$f(\psi)$is the factor related to the soil moisture condition. Soil water potential inversely affects the root water uptake. Soil suction relates to the soil moisture content through the soil water characteristic curve. Therefore, the soil reduction factor is a function of moisture content of soil (Indraratna et al. 2008; Fatahi et al. 2009). A model suggested by Feddes et al. (1974) for root water uptake reduction factor in relation to soil moisture content is shown in Figure 4,where θ_w is the moisture content at wilting point, θ_d is the minimum moisture content at $S = S_{max}$, θ_{an} is the maximum water content at maximum root water uptake. Tree physiology also affects the transpiration and leaf area, number of stomata in leaf and other biological features of tree control transpiration

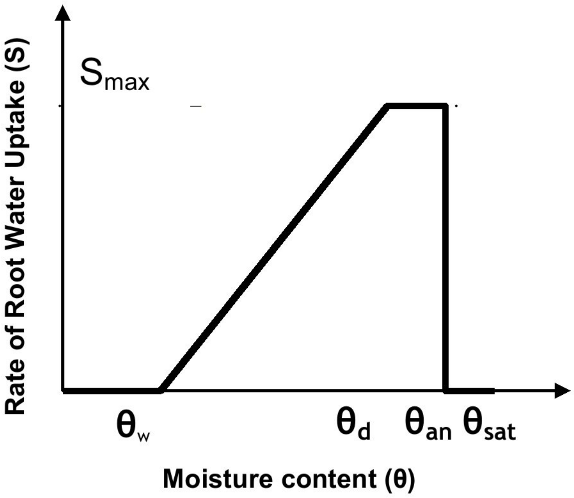


Figure 4 The water uptake – moisture content relationship (modified after Feddes et al. 1974)

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

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

where k is hydraulic conductivity ψ is soil suction, z is vertical co-ordinate and t is time. S(*x,y,z,t*) is root water uptake. Above equation can be applied for homogeneous as well as heterogeneous media.

3 MECHANICAL STRENGTHENING INDUCED BY ROOTS

Tree roots are potentially capable of binding the soil matrix together. Therefore, it gives the fibrous effect to the soil, controls the erosion control and prevents shallow failures within 1.5-2.0m (Bache et al. 1989). Moreover, large tree roots are capable of providing anchoring effect to the soil. The amount of root materials present in the shear plane namely the Root Area Ratio (RAR) is the governing parameter of the reinforcement contribution to the soil (Operstain and Frydman 2000; Docker and Hubble 2001)

$$\text{Root Area Ratio (RAR)} = \frac{AreaofRootAlongtheShearPlane}{AreaoftheshearPlane} \tag{4}$$

The effect of tree roots on shear strength increment of soil has been discussed and examined during past few decades by various researchers. Waldron (1977) introduced a model for flexible elastic root extending vertically through a horizontal shear zone and the failure modes of the root system as stretching, slipping and breaking. Furthermore, three different shear strength increment values (ΔS) related to three failure modes were defined and several experimental coefficients relating the bond strength between root and soil, tensile strength of root and other dimensional parameters were introduced (Waldron 1977). According to Waldren and Dakessian (1981),ΔS values can be directly added to the coulomb equation since there is no change in friction angle.

$$\tau = c + \Delta S + \sigma_{\mathrm{N}}\, tan\phi \tag{5}$$

The cohesion increment in soil by tree roots can be taken as proposed by Operstain and Frydman (2000) as follows;

$$\Delta C = k_r T_r(r, z, t) \tag{6}$$

where, ΔC is apparent cohesion due to tree roots, T_r is the relative root tensile strength contribution and k_r is an experimental constant. The value of T_r is influenced by root area ratio and the tensile strength of roots and diameter. In most of the root models, the shear strength development is related to the vertically driven root. Therefore, the practical applications are limited due to the more complex spatial distribution of root systems.

Docker and Hubble (2008) carried out large number of in situ direct shear test for four Australian riparian trees and proved the ability of increasing shear strength using vegetation with empirical equations. It was observed that the amount of shear increment computed by Waldron and Dakessian (1981) model was 50% more than the experimental values. Furthermore, Docker and Hubble (2009) described two types of roots systems according to the generated shear resistance against the block displacement. Figure 6(a) shows two types of root systems and Figure 6(b) displays shear resistance variation of the two types.

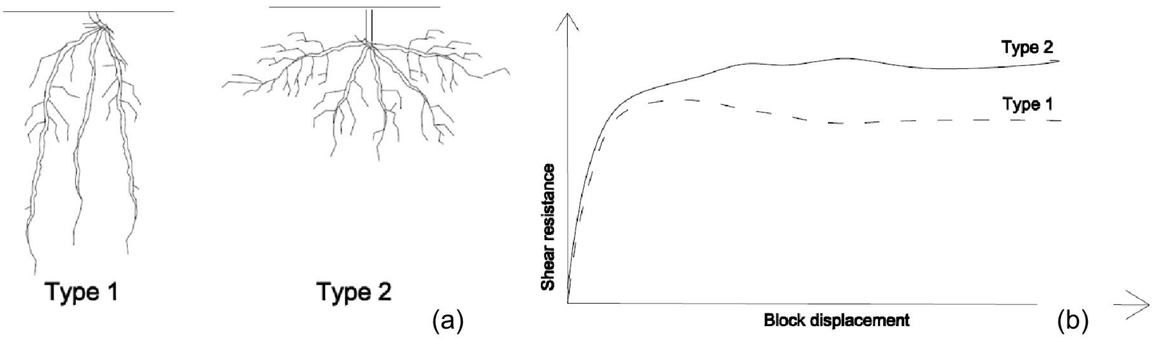
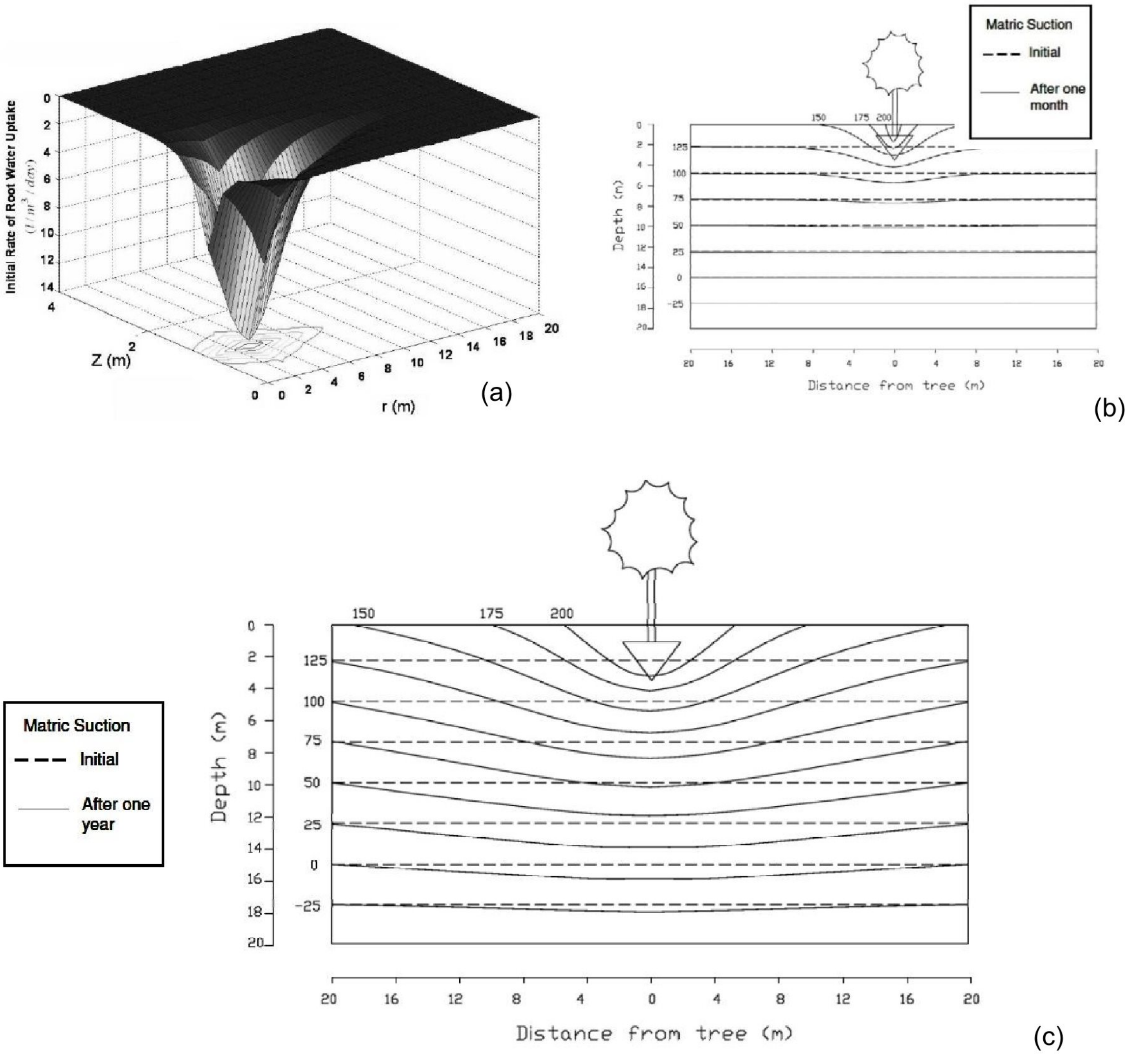


Figure 6 (a) The distinct root morphology through an in-situ shear test-block (b) Diagrammatic representation of two generally distinct root system behaviours at direct shearing (modified after Docker and Hubble 2009)

4 RESULTS AND DISCUSSION

Initial rate of root water uptake for the parameters of *Poplar tree* was computed by Fatahi (2007) using to the Eq.1 and results are shown in Figure 7(a). Furthermore, two dimensional finite element analysis has been conducted by Fatahi (2007) for given soil parameters using governing equations and the developed model verification was done for several case studies. Figures 7(b) and 7(c) show the suction values computed using ABAQUS finite element model for the parameters of Fredlund and Hung's (2001) analysis.



(a)

(b)

(c)

Figure 7 (a) Initial distribution of root water uptake of Popler tree (b) Variation of Matric suction after one month. (Fatahi 2007) (c) Variation of Matric suction after one year. (Fatahi 2007)

It is certain that most of the time sub soil remains partially saturated while depth and degree of saturation of the vadose zone are increased by the presence of mature trees. As a result of that, the parameters developed for mechanical strengthening for saturated condition are not realistic. Therefore, a combined effect has to be taken into account and parameters should be defined accordingly. Figure 8(a) gives a general understanding of the improvement in subsoil structure due to the combined effect. Soil element A in Figure 8(a) is directly under the Railway ballast and soil element B is in the root zone. General unsaturated soil mechanics theories are valid for soil element A and therefore Eq. 7 (Fredlund et al. 2012) can be used.

$$\tau = c^{'} + (\sigma_n - u_a)tan\phi^{'} + (u_a - u_w)\ [tan\phi^{'}\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)] \tag{7}$$

where, u_a and u_w are pore air and water pressures; θ_s, θ_r, and θ are saturated, residual and instant volumetric water contents and all the other symbols have their usual meaning.

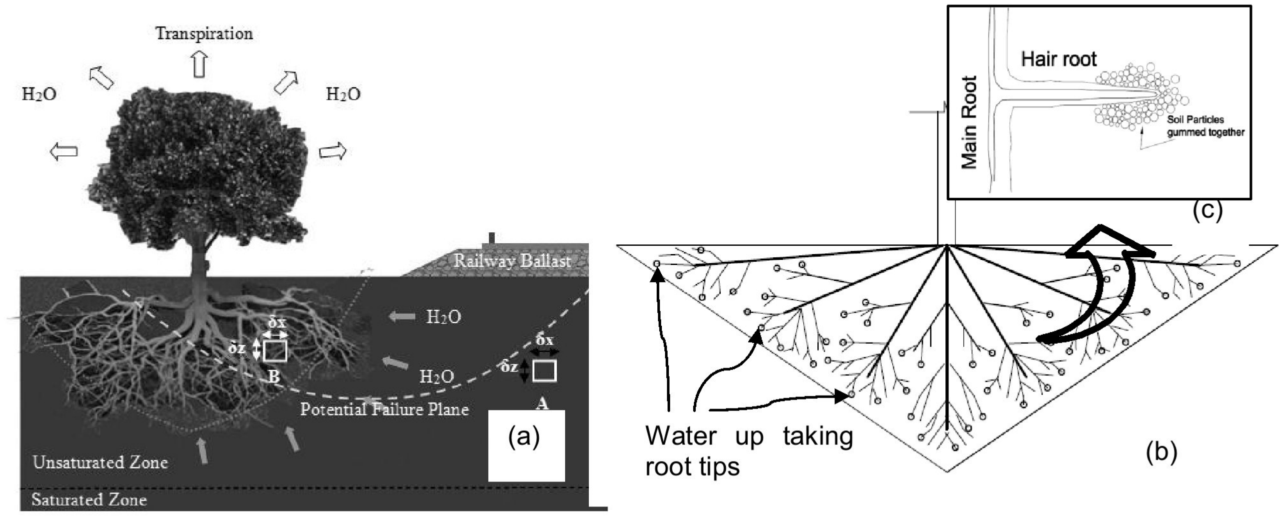


Figure 8 (a) Schematic diagram of root water uptake process and root reinforcement, (b) Schematic diagram of root system with distribution of water up-taking active root tips, (c) Enlarged root tip.

The θ value in Eq. 7 changes with time due to root water uptake and the following equation can be derived considering Eq. 3 and Reynolds differential transport theorem.

$$\frac{\partial\theta}{\partial t} = \nabla.(k\nabla\psi) - \theta\frac{\partial k}{\partial z} - dS(x,y,z,t) + dI(x,y,z,t) \qquad (8)$$

In above equation *S* represents the root water uptake sink term and *I* is the irrigation source term. The θ is the volumetric moisture content; k is hydraulic conductivity and ψ is matric suction. The usual soil water characteristic curve (SWCC) can be used for element 'A' (Figure 7a), whereas element 'B' has a great effect from root suction and root reinforcement since it is in the root zone of tree. Therefore, the description of the unsaturated soil characteristics which relies on the SWCC cannot be directly applied for element 'B'. Furthermore, the stiffness of the root zone results in an increase of shear strength in soil adjacent to element A. Therefore it is identified as a "shear capacity" of the root area zone which acts as an external stiffener with the effect from root reinforcement and suction.

Figure 7(b) shows a schematic diagram of the root zone and water uptake points. According to the enlarged view of root tip in figure 7(c) and according to the classical botanical understanding, process of osmosis at the root tip, binds the soil matrix together. Therefore, the failure patterns described in section 3, may be altered such that it governs by the process of osmosis at root tip. The suction changes the bond strength between root and soil as well as it alters the material properties of root. In this case the failure of root system due to slipping, stretching, breaking or pulling out with soil annulus are greatly affected by suction induced by tree roots as well as the adjacent soil suction. Considering all the above facts, computing the effects from root reinforcement and suction separately and superimposing them may not give realistic answers since suction has an influence on root reinforcement.

5 CONCLUSIONS

Tree roots can be used economically in subgrade improvement after an effective analysis of subsequent effects. Past developed models to compute root based suction and the root reinforcement effect have been contributed considerably for the sub grade improvement, however as described in this paper a comprehensive model which consist of mechanical strengthening as well as root based suction is vital, to have more realistic results. Moreover, most of the trees are not capable of providing the sub-soil improvement due to their shallow root system and deciduous behaviour. Therefore, it is essential to select the most appropriate plant i.e. good root system and evergreen. It was shown that it is discernible that the spatial distribution of root has a major role in reinforcing soil. The true tree root system depends on the environmental factors. Therefore, for practical usage, it is essential to compute the parameters considering environmental factors for selected tree species. The model of the shear capacity of tree root zone should comprise the coupling effect of mechanical strengthening of roots and suction and other parameters developed for selected trees. Developing more generalized equations despite the tree species and initial growing condition may not give realistic answers.

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