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Numerical prediction of unsaturated ground behavior influenced by vegetation and vacuum consolidation

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ABSTRACT: Bioengineering including native vegetation is an ancient method of improving the stability of slopes. In modern railway engineering, this technique is re-captured for increasing the soil stiffness and shear strength of subgrade beneath rail tracks. Currently this practice has become increasingly popular in Australia for stabilising railway corridors built over expansive clays and compressive soft soils. This paper looks at the stabilisation role by suction generated by both the natural vegetation and the artificial vacuum application using the numerical analysis. For demonstrating the role of native vegetation, a mathematical model for the rate of root water uptake was incorporated in the analysis. The soil moisture content distribution and the soil matric suction profile adjacent to the tree were numerically captured based on the general effective stress theory of unsaturated soil. For vacuum application, the equivalent plane strain theory was employed to simulate radial consolidation and artificially applied suction. The performance of both techniques on track constructed on soft formation was discussed and compared in terms of settlement and associated pore pressure.

KEYWORDS: Bio-engineering, Numerical analysis, Vacuum consolidation, Vertical drains

1 INTRODUCTION

In Australia, the railway system plays a vital role in transporting bulk commodities to ports, conveying passengers and transporting freight along major corridors. Rail tracks are typically constructed on compacted ballast bed, which overlies on natural subsoil (subgrade). The subgrade is a naturally deposited soil, fill material or a combination of both. Its primary purpose is to provide a stable platform to the track. In the coastal areas, the rail tracks are built on soft and compressible formation soils. The passage of heavy haul trains with considerable imposed train loads over these deposits causes excessive track settlement and significant reduction in the load bearing capacity. During both static and cyclic (repeated) loading, high volumes of plastic clays can sustain high excess pore water pressures which, in turn, lead to an excessive track deformation and overall track failure (Indraratna et al. 1992). Therefore, it is imperative to determine appropriate ground improvement methods for increasing the stiffness of soft subgrade. In this paper, the effects of 2 methods (e.g. (a) planting trees along the railway corridors and (b) applying prefabricated vertical drains (PVDs) with vacuum preloading) are compared using a numerical model.

To provide additional suction in the soft ground, tree roots have been considered as an effective form of natural soil reinforcement apart from dissipating the excess pore water pressure, and generate sufficient matric suction to increase the shear strength of the surrounding soil (Fatahi et al. 2006). In Australia, native vegetation has been grown along rail corridors. During transpiration, the loss of moisture from the soil may be divided as: (a) water used for metabolism in plant tissues, and (b) water transpired to the atmosphere from the canopy (foliage). This remediation technique allows coastal structures such as transport systems, embankments and tall buildings to be more stable under large static and cyclic loads.

Application of vacuum load via PVDs can further accelerate the rate of settlement via suction generated at the soil drain interface, generally compensating for the adverse effects of smear and well resistance (Indraratna et al. 2005, Rujikiatkamjorn et al. 2008). Installation of PVDs can reduce the consolidation period significantly by reducing the radial drainage path length, as the preloading time is inversely proportional to the square of the length of the drainage path (Hansbo 1981; Indraratna and Redana 2000). Indraratna et al. (2010) demonstrated that the application of PVDs curtails the build-up pore pressure, thereby enhancing track stability.

2 NUMERICAL MODELING

2.1 *Root water uptake model*

In order to quantify pore pressure dissipation and induced matric suction, Indraratna et al. (2006) introduced an appropriate mathematical model for considering soil suction, root density and potential transpiration (Fig. 1).

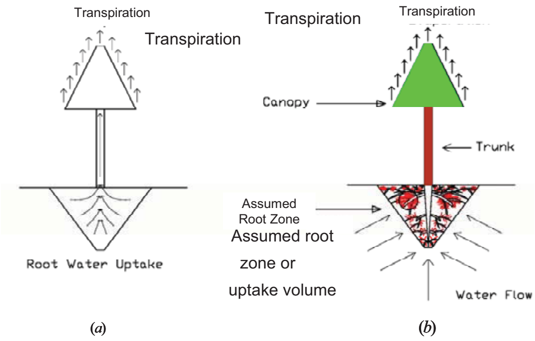

Figure 1. Schematic sketch of soil–plant–atmosphere equilibrium: (a) transpiration; (b) soil–plant–atmosphere interaction (Indraratna et al., 2006).

The important parameter for estimating the transpiration rate is the rate of root water uptake, which can be determined from soil suction, root distribution and potential transpiration rate. The formulation of these parameters is described below (Indraratna et al. 2006):

2.1.1 *Soil suction*

Soil suction reduces the free water movement towards the root zone and affects the transpiration rate. The root water uptake ($S(x,y,z,t)$) can be determined by a combined function of the maximum possible root water uptake, $S_{\max}$, and matric suction, ψ :

$$S(x,y,z,t) = S_{\max}(x,y,z,t)\, f(\psi) \tag{1}$$

where, $S(x,y,z,t)$ = the root water uptake at point (x,y,z) at time t. and $f(\psi)$ is the soil suction factor, which can be calculated using the formulations presented by Feddes et al. (1978).

2.1.2 *Root distribution*

In the development of the model, the geometric slope of the root zone is determined, based on the field observation of typical root cross sections. The intensity and distribution of transpiration within the root zone varies with the root density, hence,

$$S(x,y,z,t) = f(\psi)G(\beta)F(T_P) \tag{2}$$

where, $G(\beta)$ is a function of the root density distribution, $F(T_P)$ is the potential transpiration distribution function, and $\beta(x,y,z,t)$ is the root density. Further details about the root distribution function ($G(\beta)$) has been presented in Fatahi et al. (2009, 2010).

2.1.3 *Potential transpiration*

The potential transpiration is an evaporation of water from plant cells to the environment. Assuming that the soil moisture content is not restricted, the potential transpiration can be determined by:

$$T_P = ET_P - E_P \tag{3}$$

where, T_P is overall transpiration, ET_P is the potential evapo-transpiration (both tree and soil), and E_P is the potential evaporation from the soil surface. It is well recognised that the potential transpiration is not distributed uniformly within the root zone because of the root resistance term, and according to Indraratna et al. (2006), a linear distribution with depth for potential transpiration is a more appropriate distribution.

To evaluate the strength of the foundation, the finite element program ABAQUS was employed to simulate the soil suction distribution generated by transpiration. Equations (1)-(3) are incorporated as a sub-routine in ABAQUS supplementing the effective stress-based equations. In following section, the vacuum consolidation mechanism is described with equivalent plane strain matching procedure.

2.2 *Vacuum consolidation model*

The vacuum preloading method was originally proposed in Sweden by Kjellman (1952) for cardboard wick drains. It has been used extensively to accelerate the consolidation process of soft ground, such as Philadelphia International Airport, USA and Tianjin port, China (Holtan, 1965 and Yan and Chu, 2003, Rujikiatkamjorn et al. 2008). In soft formation area, where a high surcharge embankment cannot be constructed without affecting stability, the vacuum application is preferable. Prefabricated vertical drains (PVD) has also been used to facilitate the distribution of vacuum (suction) pressure to deep subsoil layer, thereby increasing the consolidation rate (e.g. Rujikiatkamjorn and Indraratna 2010, Chu et al. 2000). The mechanism of the vacuum preloading can be described diagrams provided by Indraratna et al. (2005) (Fig. 2). The effective stress increases through vacuum load while the total stress remains constant.

For multi-drain simulation, the plane strain finite element analysis can be readily adapted to most field situations. Nevertheless, realistic field predictions require the axisymmetric properties to be converted to an equivalent 2D plane strain condition, especially with regard to the permeability coefficients and drain geometry (Indraratna et al. 2005). The plane strain analysis can also accommodate vacuum preloading in conjunction with vertical drains. Indraratna et al. (2005) proposed the equivalent plane strain approach for the simulation of vacuum pressure for the vertical drain system.

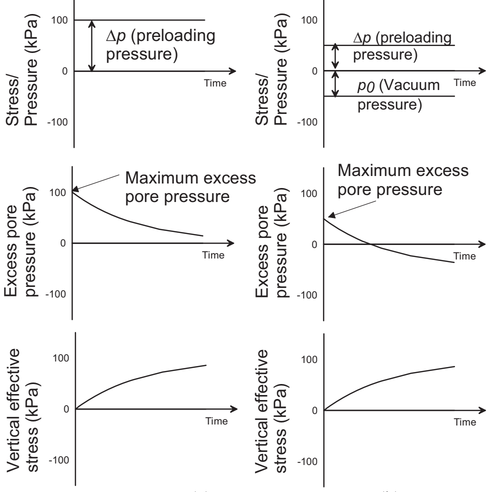

Figure 2. Consolidation process: (a) conventional loading (b) idealised vacuum preloading (Indraratna et al. 2005)

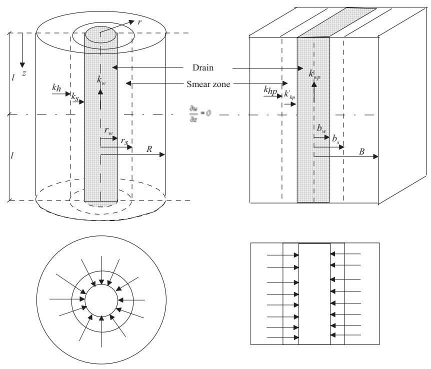

Figure 3. Conversion of an axisymmetric unit cell into plane strain condition (after Indraratna et al. 2005)

The influence of smear effect can be modelled by the ratio of the smear zone permeability to the undisturbed permeability, as follows:

$$\frac{k'_{hp}}{k_{hp}}=\frac{\beta}{\frac{k_{hp}}{k_h}\left[\ln\left(\frac{n}{s}\right)+\left(\frac{k_h}{k'_h}\right)\ln(s)-0.75\right]-\alpha} \tag{4}$$

$$\alpha=\frac{2}{3}-\frac{2b_s}{B}\left(1-\frac{b_s}{B}+\frac{b_s^2}{3B^2}\right) \tag{4a}$$

$$\beta=\frac{1}{B^2}(b_s-b_w)^2+\frac{b_s}{3B^3}\left(3b_w^2-b_s^2\right) \tag{4b}$$

where, k_{hp} and k'_{hp} are permeability of soil in undisturbed and smear zone, respectively for plane strain condition

If smear and well resistance effects are ignored in the above expression, then the simplified ratio of plane strain to axisymmetric permeability is readily obtained, as also proposed earlier by Hird et al. (1992), as follows:

$$\frac{k_{hp}}{k_h}=\frac{0.67}{[\ln(n)-0.75]} \tag{5}$$

For vacuum preloading, the equivalent vacuum pressures in plane strain and axisymmetric are the same.

3 NUMERICAL MODELING

A two-dimensional finite element analysis has been employed to study the ground displacement in the vicinity of railway lines. Firstly, the ground behavior beneath the rail track in plane-strain conditions has been modeled. Subsequently, the effect of two rows of 11m high Eucalyptus largiflorens (black box) trees grown adjacent to track has been investigated and compared with the subgrade soil stabilized using 3 rows of prefabricated vertical drains (PVDs) with vacuum preloading along rail track. The finite element mesh and specified boundary conditions are shown in Figure 4.

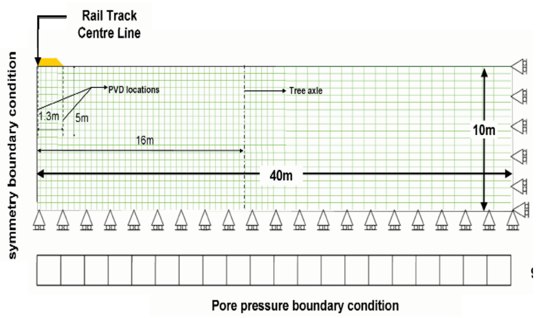

Figure 4. Geometry and boundary conditions of the finite element model

Because of symmetry, a no flow boundary was applied to the left hand side of mesh in Figure 4. It is assumed that a "no water in-flow" condition is applied to the soil surface. The mesh employed in this analysis is based on bi-linear strain quadrilateral elements (CPE4P) with 4 displacement and pore pressure nodes at the corner of each element. The total FE mesh contains 4960 nodes and 4800 elements.

In railway engineering, repeated train loading is usually modeled as an equivalent static load corrected by a dynamic amplification factor. The value of impact load factor may be changed according to the field conditions simulated on track (Esveld, 2001). In this study, a static load of 80kPa with an appropriate impact factor of 1.3 has been applied to represent 25 tones axle loads. All specifications of the tree and vacuum consolidation used in the analysis are tabulated in Tables 1 and 2.

Table 1 Parameters of interaction between tree and ground of a Black Box tree at Miram (after Fatahi et al. 2009)

Parameter	Measured Value	Comments
$r_{\max}$	20m	Maximum lateral distance of root zone, estimated from field observation
$z_{\max}$	3m	Maximum possible root zone depth, estimated from field observations
r_0	8.5m	Radial coordinate of the maximum root density point
z_0	1.2m	Vertical coordinate of the maximum root density point
$\beta_{f\cdot\max}$	659000 m^{-2}	Maximum root density, measured according to organic content
k_1	0.35	Lateral root density distribution factor, measured according to organic content
k_2	0.55	Vertical root density distribution factor measured according to organic content
ψ_w	1500 kPa	Wilting point suction, estimated from field measurements
ψ_{an}	4.9kPa	Soil suction at anaerobiosis point, clayey soil with air content of 0.04 (Feddes et al. 1976)
T_p	80 l/day	Potential Transpiration, estimated from Slavich et al. (1998) and Jolly and Walker (1996)

The root water uptake model was included in the numerical scheme via Visual Fortran subroutines. The main subroutine includes the rate of root water uptake as a moisture flux boundary applied to the four sides of every element within the root zone. In other words, Equation (1), incorporating Equations (2) and (3), has been used in the numerical model as boundary flux to determine the rate of root water uptake within the root zone at each increment of time. To simulate the effect of 10 m long prefabricated vertical drains with a maximum possible vacuum preloading pressure of 100kPa (theoretical value), the pore water pressure at PVD boundaries has been set to -90kPa for practical purpose. The equivalent permeability was determined from Eqs. (4) and (5).

Table 2 Parameter values assumed in the finite element analysis of the case study

(a) Modified Cam-clay Parameters for Vacuum consolidation (Normally consolidated ground)

Parameter	**Value**
γ_d	11 kN/m^3
$\lambda/(1+e_0)$	0.15
$\kappa/(1+e_0)$	0.03
φ'	25 degrees
c'	10 kPa
ν	0.30
k	5x10^{-5} m/s
e_0	1.1
OCR	1

(b) Tree (Overconsolidated ground)

Parameter	**Value**
γ_d	11 kN/m^3
$\lambda/(1+e_0)$	0.15
$\kappa/(1+e_0)$	0.03
φ'	35 degrees
c'	15 kPa
ν	0.30
k	5x10^{-5} m/s
e_0	1.1
OCR	6 (root zone)

4 RESULTS AND DISCUSSIONS

Figure 4 illustrates the contours of matric suction generated in the vicinity of the rail track induced by both root water uptake (Fig. 4a) and vacuum preloading (Fig. 4b). According to Fig. 4a, the maximum root-based matric suction (1500kPa) can occur away from the track centre line even the tree has been planted 16m away from the railway. It can be seen that there are two zones of maximum matric suction on both sides of the tree. In contrast, the theoretical maximum of soil matric suction induced by vacuum preloading is only 90 kPa (Fig. 4b), which occurs between two rows of PVDs only underneath the rail track. In both cases, the induced soil matric suction results in increased effective stresses and hence soil consolidation.

Figures 5 and 6 indicate the settlement contours for the top 5m of the soil layers due to tree transpiration and vacuum pressure through PVDs, respectively. Deformation in the soil profile due to the root water uptake and vacuum pressure were predicted through a coupled flow-deformation analysis. The maximum induced settlements by root water uptake and PVDs with vacuum preloading are similar. However, the application of PVDs with vacuum preloading can induce more consolidation settlement directly underneath the rail track in comparison to a row of trees 16m away. In spite of the fact that PVDs provide only 100kPa suction, they generate more consolidation settlement than the trees, which generate 1500kPa. This is because the suction generated by tree is curtailed within root zone (within 3m depth below ground surface)

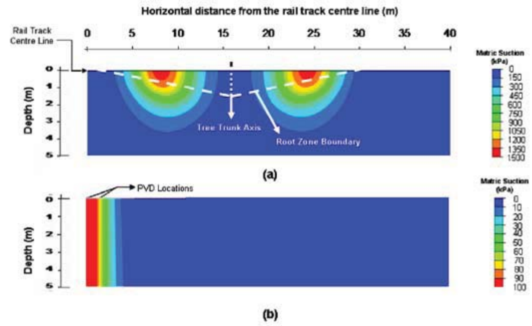

Figure 4. Contours of soil matric suction induced by (a) tree root water uptake, and (b) vacuum preloading (100kPa)

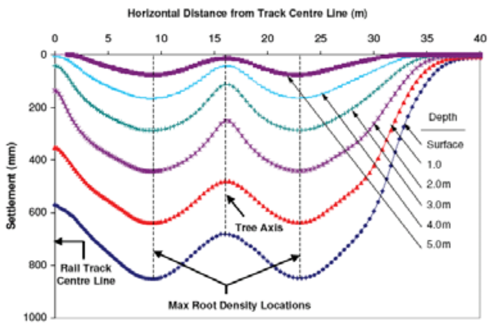

Figure 5. Contours of ground settlements in top 5m of soil layer induced by Black Box tree transpiration

This is because PVDs generate suction all along the drain length, but trees provide a very high suction (1500kPa) in the root zone and mainly around the point of maximum root length density. 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 most of primary consolidation is achieved (>95% consolidation), thereby increasing soil shear strength.

Figure 7 indicates the time-surface settlement curve at the centre line for track constructed on soft foundation under different improvement approaches namely (a) non-treated foundation, (b) native vegetation (16m away from the track centre line), and (c) application of two rows of 10m deep PVDs with 100kPa vacuum preloading. Most of the primary settlement (>90% consolidation) for the vacuum consolidation case would be after about 180 days, and almost after a year of continuous transpiration for the case of a well developed tree. As shown in Figure 7, a surface settlement of 581mm due to train load for the case of untreated soft soil after 1000 days can be reduced to only160mm by planting trees along the railway line; or it can be reduced further to 60mm by vacuum pressure application.

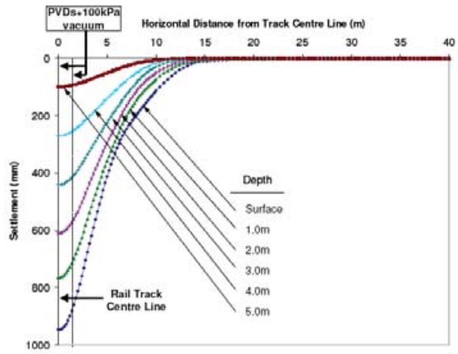

Figure 6. Contours of ground settlements in top 5m of soil layer induced by PVDs with 100kPa Vacuum Pressure

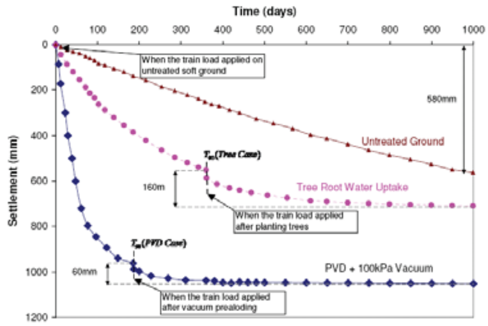

Figure 7. Time-surface settlement curves under various improvement schemes.

The shear strength profile of the soil, before treatment (very soft normally consolidated soil), and after treatment with planting a Black Box tree and prefabricated vertical drains with vacuum preloading have been illustrated in Figure 8.

As Figure 8 indicates, both treatments methods (planting Black Box tree and PVD with vacuum preloading) increase the undrained shear strength of the soil. As the root - based suction is high in the top soil layers (within the root zone), Black Box tree improves the shear strength of top soil layer more than PVDs. In addition, as the tree root water uptake is a continuous process, but vacuum pressure will be removed after end of consolidation, the effective stresses and shear strength would be higher in the case of root water uptake. However, as Figure 8 illustrates, after heavy rainfall, soil looses the matric suction and consequently the effective stresses and the shear strength decrease. In a similar way, the soil shear strength is higher when the vacuum pump is in operation at a suction pressure of 100kPa, in comparison to the shear strength after vacuum preloading.

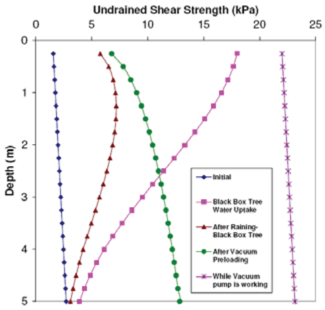

Figure 8. Soil undrained shear strength under the track centre line after different treatments

5 CONCLUSION

The action of a single tree on improving the soil behaviour has been compared to a vertical drain with applied suction (vacuum pressure). Two-dimensional multi-drain finite element analyses (ABAQUS) were executed to evaluate the consolidation of soil under both techniques. It can be seen that root water uptake and associated matric suction is analogous to a prefabricated vertical drain with vacuum preloading. It shows that suction generated by both techniques can reduce significant ground settlement due to train load.

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. However, it should be explained that trees need time to grow and reach to an acceptable performance situation. Results of this study demonstrate that railway infrastructure can be improved by identifying and managing surrounding vegetation.

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