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SOFT SOIL IMPROVEMENT INDUCED BY TREE ROOT SUCTION

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ABSTRACT

Bioengineering aspects of native vegetation are currently being evolved to improve soil stiffness, slope stabilisation, and erosion control. Tree roots provide three stabilising functions: (a) reinforcement of the soil, (b) dissipation of excess pore pressures and (c) establishing sufficient matric suction to increase the shear strength. The effects of vegetation on soil matric suction, shrinkage and ground settlement are discussed in this paper. A mathematical model for the rate of root water uptake that considers ground conditions, type of vegetation and climatic parameters has been developed. A conical shape is considered to represent the geometry of the tree root zone. Based on this proposed model, the distribution of the moisture and the matric suction profile adjacent to the tree are numerically analysed. Field measurements taken from literature published previously are compared with the authors' numerical model. The predicted results, calculated based on soil, plant, and atmospheric parameters contained in the numerical model, compared favourably with the measured results, justifying the assumptions upon which the model has been developed. The findings of this study indicate that due to significant changes in soil moisture content induced by tree roots, the shear strength of the soil will be enhanced. It is desirable to consider the influence zone of tree roots and the improved soil properties in modern geotechnical designs, benefiting from native vegetation.

1 INTRODUCTION

All over the world, soil conditions on construction sites have become worse than ever due to the overpopulation in the metropolitan areas. These conditions have compelled engineers to construct earth structures, major highways, and railways over expansive clays and compressive clay deposits. Australia's railway network covers a vast area of land over very variable land forms and soil types and the freight transported is growing rapidly. The maintenance expenditure is influenced greatly by the large distances covered and the poor quality of the subgrade encountered and therefore there is pressure to find appropriate methods to reduce the maintenance cost. Following heavy rains there will be water collection in depressions underneath the rail tracks resulting in further track settlement and hazardous railway problems.

New maintenance observations show that where there are trees beside railway tracks, their localised, undrained failure is minimised. Using native vegetation in the remote railway lines in Australia to stabilise existing railway corridors built over expansive clays and compressive soft soils has become increasingly popular (Figure 1). Properly selected and implemented vegetation, including native trees and shrubs, can reduce soil moisture by root water uptake. Moreover, vegetation can increase the shear strength and stiffness of soil by increasing matric suction and control erosion as a secondary effect.

In modelling of vadose zone behaviour influenced by vegetation, detailed consideration of root water uptake is required to develop a realistic model. Although the currently existing design standards such as Uniform Building Code (1997) and Standards Australia (1996) provide guidelines for design and construction of footings and structures on expansive clays, none of them provide any guideline on how ground desiccation caused by native vegetation should be incorporated in the designs. Blight (2005) drew the conclusion that most past research on influence of vegetation on ground has been opportunistic and unplanned and also the presented models have been very simple or have not been validated strongly using field data. The existing models, predicting effects of vegetation on the ground, only consider the root reinforcement effects or only consider a very simplified model for the tree root water uptake. For example, Fredlund and Hung (2001) in their analysis to predict volume change in expansive soils as results of vegetation, did not consider the realistic root zone and assumed that the root water uptake rate was time independent, which is not a realistic assumption. Biddle (1998) reported a comprehensive field observations for predicting pattern of soil drying in the proximity of trees on clay soils associated with 60 different cases. Although tree root density distribution influences the pattern of moisture redistribution in vicinity of a tree, Biddle (1998) did not include the root distribution data in his report. Cameron (2001) recorded that the suction under rows of eucalypt trees in Australia may exceed that away from the trees down to depths of 6 m or more. Cameron (2001) and Jaksa *et al.* (2002) recommended suction boundaries for top 6 m of soil strata according to the field measurements. Their studies attempted to overcome the shortcomings of guidelines for footing design influenced by trees. However, their guidelines can not distinguish suction increase or decrease by depth and lateral distance and consequently soil shrinkage or swell under the specified tree specie, soil and weather conditions. They concluded that more data was required to adopt the reliable design guidelines.

After reviewing previous studies, it was decided to embark on development of a model to predict changes of soil water content in proximity of vegetation considering ground properties, vegetation specifications and atmospheric conditions. The main objective of this study is to establish a rigorous formula for estimating root water uptake, and accordingly to develop an integrated two-dimensional transient FE model considering soil water extraction by roots within vadose zone to simulate the ground under the influence of vegetation. The results are then compared with field measurements to verify the numerical predictions.

2 THEORETICAL CONSIDERATIONS

The main factor for estimating the rate of transpiration is the rate of root water uptake, which in turns depends on the geological, hydrological, and meteorological conditions, hence:

$$T(t) = \int_{V(t)} S(x,y,z,t)dV \tag{1}$$

where, $T(t)$ is the transpiration rate at time t, $S(x,y,z,t)$ is the rate of the root water uptake at point (x,y,z) at time t, and if $V(t)$ is the volume of root zone at time t, dV denotes a small volumetric change.

The details of each single root and its interaction with the surrounding soil is required to identify the microscopic interaction between the soil and root system. In this study a macroscopic approach is adopted, which considers the integrated properties of the entire root system, assuming that both the soil and roots form a continuous media. Therefore, the root water uptake is considered as a volumetric sink term in the flow continuity equation, which can be defined as the volume of water extracted per unit bulk volume of soil per unit time. The soil water flow differential equation, including the sink term, $S(x,y,z,t)$, can then be written as:

$$\frac{\partial \theta}{\partial t} = \nabla.(k\nabla \psi) - \frac{\partial k}{\partial z} - S(x,y,z,t) \tag{2}$$

where, $\theta\ (=V_W/V)$ is the volumetric moisture content, (V_w = volume of water, V = total volume), ∇ is the divergence vector, ψ is the soil suction, k is the hydraulic conductivity, and z is the vertical coordinate (downward is positive).

The soil suction, root density distribution, and potential transpiration, which are three independent features, may be combined to establish an appropriate analytical solution for estimating the rate of root water uptake. As suggested by Indraratna *et al.* (2006), it can be assumed that:

$$S(x,y,z,t) = f(\psi).G(\beta).F(T_P) \tag{3}$$

where, $G(\beta)$ is the root density factor, $f(\psi)$ is the soil suction factor, and $F(T_P)$ is the potential transpiration factor.

To calculate $f(\psi)$, different approaches have been recommended by various researchers. The simplified equation suggested by Feddes *et al.* (1978) is used to determine the effect of suction.

$$\begin{cases} f(\psi) = 0 & \psi < \psi_{an} \\ f(\psi) = 1 & \psi_{an} \le \psi < \psi_d \\ f(\psi) = \dfrac{\psi_w - \psi}{\psi_w - \psi_d} & \psi_d \le \psi < \psi_w \\ f(\psi) = 0 & \psi_w \le \psi \end{cases} \tag{4}$$

where, ψ_w is the soil suction at wilting point, ψ_d is the highest value of ψ at $S = S_{max}$ and ψ_{an} is the lowest value of ψ at $S = S_{max}$, where S_{max} is the maximum rate of root water uptake.

Landsberg (1999) proposed that the total cross sectional area of roots, including the depth and distance from the trunk, can be determined by an exponential relationship. It is assumed by symmetry that the maximum root density lies on a circle with $r = r_0$ at a depth of $z = z_0$ (see Figure 2), and also that the root density decreases exponentially from this maximum value both vertically and radially. Thus, the root density function may be written as:

$$\beta(r,z,t) = \beta_{max}(t).e^{-k_1|z-z_0(t)|-k_2|r-r_0(t)|} \tag{5}$$

where, $\beta_{max}(t)$ is the maximum root density at time t, and k_1 and k_2 are two empirical coefficients depending on the type and system of tree root.

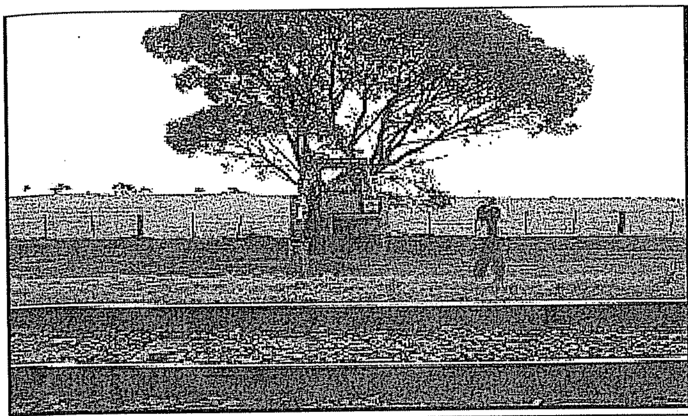

Figure 1: Site investigation to study the influence of a Black Box tree on the rail track at Miram site, Victoria, Australia

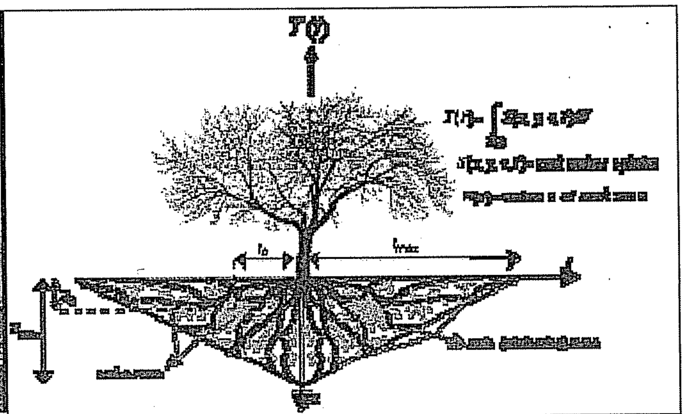

Figure 2: Schematic sketch of tree root zone.

For a given transpiration rate, the rate of water uptake from any particular unit volume of wet soil is proportional to β. As suggested by Landsberg (1999), this relationship is nonlinear. Based on agronomical research, an asymptotic relationship may be assumed for the root water uptake. Nevertheless, there is an uncertainty in this relationship when the roots become widely separated, which can often be the case if the roots penetrate deeply into the soil.

Considering a hyperbolic tangent function that represents a nonlinear-asymptotic curve, the following equation is suggested by the authors for the root density factor, $G(\beta)$,

$$G(\beta) = \frac{\tanh(k_3 \beta)}{\int_{V(t)} \tanh(k_3 \beta) dV} \tag{6}$$

In the above expression, k_3 is an empirical coefficient. $G(\beta)$ is presented as a normalised function, where $\int_{V(t)} G(\beta) dV = 1$.

Referring to the model proposed by Nimah and Hanks (1973), it can be inferred that with depth, the potential transpiration is not distributed uniformly within the root zone and therefore a linear distribution for potential transpiration is more appropriate. Accordingly, Equation (7) is derived to take the effect of potential transpiration into account:

$$F(T_P) = \frac{T_P (1 + k_4.z_{max} - k_4.z)}{\int_{V(t)} G(\beta)(1 + k_4.z_{max} - k_4.z) dV} \tag{7}$$

where, T_p is the rate of potential transpiration and k_4 is an empirical coefficient to represent the effect of depth on potential transpiration distribution. The denominator of Equation (7) represents the transpiration mass balance.

3 VERIFICATION OF THE PROPOSED MODEL USING FE ANALYSIS

To verify the model, a case history reported by Biddle (1983) has been considered for a lime tree grown in Boulder clay. The estimated parameters based on the available literature are shown in Table 1. Figure 3 illustrates the mesh and element geometry and boundary conditions of the finite element model built in ABAQUS code. A two-dimensional plane strain mesh employing 4-node bilinear displacement and pore pressure elements (CPE4P) was considered. The developed theoretical model representing the rate of root water uptake distribution within the root zone was included in the FE analysis through appropriate Visual Fortran subroutines.

The boundary conditions of the finite element model are illustrated schematically in Figure 3. The flux boundary at the surface is controlled by both climatic conditions and soil properties. It is assumed in this study that rainfall and evaporation are in balance and thus a "no water in-flow" condition is applied at the surface.

This numerical analysis is based on the basic effective stress theory of unsaturated soils incorporated in the ABAQUS finite element code. The effective stress in unsaturated soils is given by (Bishop, 1959):

$$\sigma'_{ij} = \sigma_{ij} - u_a \delta_{ij} + \chi (u_a - u_w) \delta_{ij} \tag{8}$$

where, σ'_{ij} is the effective stress of a point on a solid skeleton, σ_{ij} is the total stress in the porous medium at the point, u_a is the pore air pressure, u_w is the pore water pressure, δ_{ij} is Kronecker's delta ($\delta_{ij} = 1$ when $i = j$ and $\delta_{ij} = 0$ when $i \neq j$), and χ is the effective stress parameter attaining a value of unity for saturated soils and zero for dry soils.

Table 1: Parameters applied in the finite element analysis.

Parameter	Value	Reference/ Comments
ψ_{an}	4.9 kPa	Feddes *et al.* (1978); Clayey soil with air content of 0.04
ψ_w	1500 kPa	Feddes *et al.* (1978); $1500 < \psi_w < 2000$ kPa
ψ_d	40 kPa	Feddes *et al.* (1978); $40 < \psi_d < 80$ kPa
γ	21 kN/m^3	Powrie *et al.* (1992); Typical value for Boulder clay
$r_{\max}$	9m	Biddle (1983); Estimated from field measurements $(7m < r_{\max} < 11m)$
$z_{\max}$	1.5m	Biddle (1983); Estimated from field measurements
k_s	10^{-10} m/s	Lehane and Simpson (2000); Typical value for Boulder clay
PI	23	Biddle (1983); Measured
e_0	0.60	Powrie *et al.* (1992); Typical value for Boulder clay
C_c	0.13	Skempton (1944); Typical value for Boulder clay
r_0	6 m	Radial coordinate of the maximum root density point
z_0	0.50 m	Vertical coordinate of the maximum root density point
$\beta_{\max}(t)$	25 m-2	Taken from the general shape or root suggested by Landsberg (1999)
k_3	0.0874 m^{-1}	As above
k_4	0.014	Coefficient of potential transpiration distribution
k_1	10	Coefficient of vertical root distribution
k_2	0.30	Coefficient of horizontal root distribution
ν	0.30	Typical Poisson's ratio for clayey soils
T_P	3 mm/day	Rate of potential transpiration
Passing #200	55%	Typical value for Boulder clay

Bishop's effective stress concept for predicting shear strength and volume change in unsaturated soils has recently been discussed and validated by Khalili *et al.* (2004). Also, Khabbaz (1997) presented a relationship for χ as a function of matric suction and the air entry value. The degree of saturation is associated with matric suction through the soil water characteristic curve (SWCC). The air entry value, related to the soil structure, can be determined using SWCC. The soil-water characteristic curve employed in this study is shown in Figure 4.

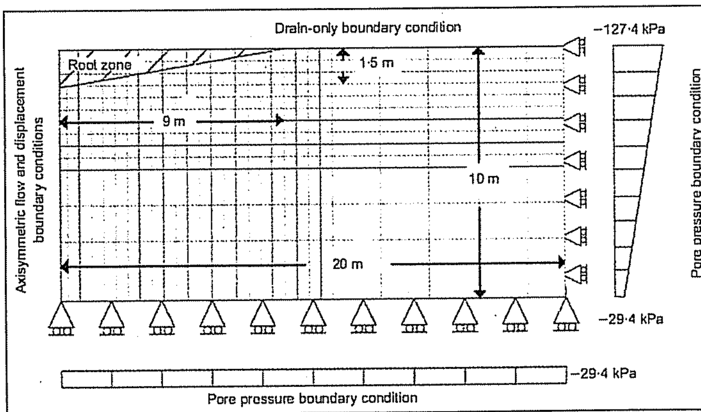

Figure 3: The geometry and boundary conditions of the model

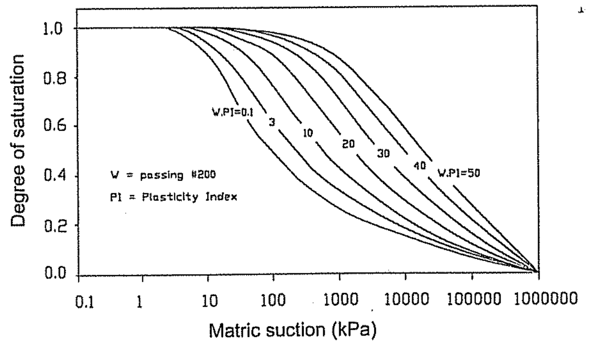

Figure 4: Predicted soil water characteristic curve based on $w \times PI$ (after Zapata *et al.*, 2000)

The finite element analysis is conducted in two stages: (i) geostatic and (ii) consolidation. The first stage is to ensure that the analysis commences from a state of equilibrium under geostatic loading. The consolidation stage is to avoid non-physical oscillations and possible divergence problems caused by non-linearities. This stage includes a transient analysis of partially saturated soil under transpiration, starting with 1-day intervals and then continued for 1–year, with continuous root water uptake.

The coefficient of unsaturated soil permeability has been calculated based on Brooks and Corey (1964), thus:

$$k = k_s(e) S_e^{\frac{2+3\lambda}{\lambda}} \tag{9}$$

where, $k_s(e)$ is the saturated coefficient of permeability estimated based on the well known Kozeney-Carman equation, S_e is the effective degree of saturation and λ $(= \Delta \log S_e / \Delta \log \psi)$ is the slope of the soil water characteristic curve on a log-log plot.

As fluid passes through a porous medium, a coupled flow-deformation analysis of unsaturated soil is required to capture the 3-phase interaction among the soil, air and water. The governing equations for pore fluid diffusion and deformation are a combination of Equation (2) and the relevant deformation equations. The soil is Boulder clay whose behaviour can be defined by

$$de^{el} = C_c \ln(\frac{p_0 + dp}{dp}) \tag{10}$$

where, de^{el} denotes the change of void ratio in the element, C_c is the compression index, p_0 is the initial mean effective stress, and dp is the mean effective stress change on the soil skeleton. The effect of osmotic suction is assumed to be negligible.

A comparison between the field measurements and the FEM predictions for moisture content reduction around the lime tree is presented in Figure 5. The numerical model is in accordance with the field observations by Biddle (1983). The main differences noted between field data and the predictions are observed at 6-8m from the trunk. This discrepancy is attributed to the simplicity of the assumed root zone shape. In addition, the foliage prevents uniform distribution of rainfall around the tree. As a result, moisture content can increase at the canopy edges, thereby further contributing to this disparity.

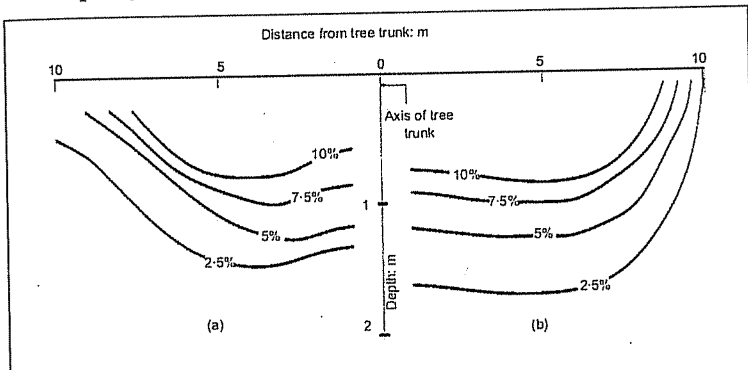

Figure 5: Contours of volumetric soil moisture content reduction (%) close to a lime tree: (a) Biddle (1983), (b) FEM predictions.

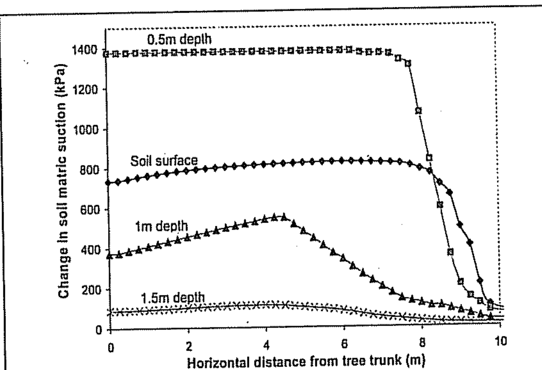

Figure 6: Predicted soil matric suction in different depths.

The maximum change in the soil matric suction from the finite element analysis (Figure 6) is found at about 0.5m depth, which coincides with the same location of the maximum root density. Also, the results show that the location of the maximum settlement tends to coincide with the points of maximum change in suction.

4 CONCLUSION

In order to investigate the effects of tree transpiration on ground condition, a numerical model based on the finite element analysis has been developed considering the coupled flow-deformation equations. The finite element mesh is formulated using partially or fully saturated soil elements, which are capable of capturing the role of unsaturated permeability and the degree of saturation at various levels of matric suction. Tree root suction was considered through the developed model which takes into account soil matric suction, distribution of root density and potential transpiration.

Existing data from previously published literature has been used to validate the analysis. It has been found that given the approximation of the assumed root geometry and model parameters, the agreement between predictions and field data is promising. Vegetation can be used close to the rail track to reduce settlement and lateral movement. The proposed root water uptake and transpiration model verifies that the suction induced by roots contributes to substantial gain shear strength. Similar to prefabricated vertical drains, roots induce good drainage, pore water pressure dissipation and in addition provide natural soil reinforcement. As the influence zone of each tree can be several meters in radius, the methodological planting of native trees along rail corridors at a practical distance away from the track is currently considered by rail organisations.

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6 REFERENCES

Biddle, P.G. (1983). Pattern of soil drying and moisture deficit in the vicinity of trees on clay soils. *Geotechnique*, 33, 2, 107-126.

Biddle, P.G. (1998). *Tree Root Damage to Buildings*. Wantage, Willowmead Publishing Ltd.

Bishop, A.W. (1959). The principle of effective stress. *Teknish Ukebadk*, Norway, No. 39, 859-863.

Blight, G. E. (2005). Desiccation of a clay by grass, bushes and trees, *Geotechnical and Geological Engineering*, Vol. 23, Springer, 697–720

Brooks, R.H., and Corey, A.T. (1964). *Hydraulic properties of porous media*. Hydrology paper3, Colorado state university, Fort Collins, Colorado

Cameron, D.A. (2001). The Extent of Soil Desiccation Near Trees in a Semi-Arid Environment, *Geotechnical and Geological Engineering*, Vol 19, Issue 3-4, pp 357 –370.

Feddes, R.A:, Kowalik, P.J. and Zaradny, H. (1978). *Simulation of field water use and crop yield*. Pudoc, the Netherlands.

Fredlund, D.G. and Hung, V.Q. (Vipulanandan C. *et al.* (EDS.).) (2001). Prediction of volume change in an expansive soil as a result of vegetation and environmental changes. *Expansive Clay Soils and Vegetative Influence on Shallow Foundations*, Geo Institute, U.S.A, 24-43.

Indraratna, B., Fatahi, B. and Khabbaz, H. (2006). Numerical analysis of matric suction effects of tree roots. *Proceedings of the Institution of Civil Engineers Geotechnical Engineering*, Vol 159 No. GE2, pp. 77–90.

Jaksa, M.B., Kaggwa, W.S. and Woodburn, J.A. (2002). Influence of large gum trees on the soil suction profile in expansive soils. *Australian Geomechanics Journal*, 37, 1, 23-33.

Knight, J.H. (Landsberg J.J. (Ed.).) (1999). Tree Water Use and its Implications in Relation to Agroforestry Systems, Appendix 2, *The Way Trees Use Water*, Rural Industries Research and Development Corporation (RIRDC), Australia, Water and Salinity Issues in Agroforestry No. 5, RIRDC Publication No. 99/37, RIRDC Project No. CSM-4A, 25-78.

Landsberg, J.J. (Landsberg J.J. (Ed.).) (1999). *Tree* Water Use and its Implications in Relation to Agroforestry Systems. *The Way Trees Use Water*, Rural Industries Research and Development Corporation (RIRDC), Australia, Water and Salinity Issues in Agroforestry No. 5, RIRDC Publication No. 99/37, RIRDC Project No. CSM-4A, 1-24.

Lehane, B.M. and Simpson, B. (2000). Modeling glacial till under triaxial conditions using a BRICK soil model. *Canadian Geotechnical J.*, 37, 1078-1088

Khabbaz H. (1997). *An effective stress theory based numerical model for flow and deformation in unsaturated soils*. PhD thesis, University of New South Wales, Sydney.

Khalili N., Geiser F. and Blight G.E. (2004). Effective stress in unsaturated soils: review with new evidence. *International Journal of Geomechanics*, 4, 2, 115-126.

Nimah, M.N., and Hanks, R.J. (1973). Model for estimating soil water, plant and atmospheric interrelations. I. description and sensitivity. Proceedings *of Soil Science Society of America*, 37, 522-527.

Powrie, W., Davies, J.N., and Britto, A.M.A (1992). Cantilever retaining wall supported by a berm during temporary work activities. *ICE conference on retaining structures*. Robinson College, Cambridge, 418-428.

Skempton, A.W. (1944). Notes on compressibility of clays. *Quarterly Journal of Geological Society*, Vol. 100, 2, 119-135.

Standards Australia. (1996). *Residential slabs and footings construction*, AS2870-1996

Uniform Building Code, (1997). *International Building Code*, International Conference of Building Official.

Zapata, C.E., Houston, W.N., Houston, S.L., and Walsh, K.D. (Shackeford *et al., Eds.*) (2000). Soil-water characteristic curve variability. *Advances in unsaturated geotechnics*. GEO-Institute, ASCE, U.S.A, 84-124.