RAINFALL EVALUATION OF ROOT WATER-UPTAKE INDUCED DEFORMATION

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ABSTRACT

A volume change was modeled as a result of matric suction change caused by vegetative induced moisture migration. Tree root water-uptake increases soil strength by increasing the soil matric suction and as well causes volume change which might be detrimental to geotechnical structure. Rainfall effects are evaluated for full cycle and simulated for periods that covers a spring/summer soil-drying phase of 6 months followed by an autumn/winter 6 month recharge phase. The effects of with and without rainfall has been incorporated into the simulation work. Generally rainfall reduces the amount of the root generated matric suction and ground movement due to recharge. From the results, vegetative induced matric suction change, induced deformation without considering rainfall effect tends to be too conservative and work of this kind is not complete without inclusion of rainfall data.

Keywords: model, rainfall evaluation, root water up-take, unsaturated soils, matric suction distribution, ground deformation.

INTRODUCTION

A change in pore pressure is accompanied by the flow of water due to pressure gradients. Thus any change in pore pressure may produce changes in water volume in the soil mass. In prediction of soil movement two fundamental stages are generally involved; an assessment of the changes in moisture conditions and the knowledge of the volumetric strains induced by these change.

It is assumed that any deformation in the soil mass takes place due to changes in the effective stress, and changes in effective stress occur due to two reasons. Firstly the effective stress may increase because of increase in the externally applied load accompanied with free drainage of water. Secondly, the effective stress might increase due to reduction in the pore pressure as a result of extraction of water from the soil mass.

The deformation of soil matrix in general soil mechanics is analyzed as a result of increase in applied load, whereas in groundwater field, the soil deformation is studied due to extraction of groundwater. In both cases, deformation takes place, because pore volume decreased. In the study of groundwater extraction it is assumed that there is no change in the applied load field, and changes occur in the effective stress due to changes in the pore pressure.

A seasonal water variation as a result of root water-uptake was measured by Biddle [1]. A simple concept of sink term for uptake was developed by Rees and Ali [2] and incorporated to two-dimensional governing equation for unsaturated soil and converted to axi-symmetrical form see Carslaw and Jaeger [3]. The capillary potential was estimate as a result of the root water-uptake was partial coupled to estimate the deformation as a result of vegetative induced matric suction changes. The effect of with and without rainfall has being incorporated into the simulation work. The model was verified with Fredlund and Hung [4] with the water-uptake validated with Biddle (1).

Nomenclature

χ	= effective stress,
u_a-u_w	= matrix suction,
σ-u_a	= net mean stress,
u_w	= pore water pressure,
σ'	= effective stress,
σ	= total effective stress,
u_w	= effective pore water pressure
S_r	=degree of saturation
V_T	= total volume of soil
V_w	= volume of water in the soil pores
K	= unsaturated hydraulic conductivity,
t	= time,
r, z	= polar coordinate,
θ	= volumetric moisture content
ψ	= capillary potential,
S(r, z)	= root water extraction function
r_r	= maximum rooting depth in the radial direction,
z_r	= maximum rooting depth,
de	= change of void ratio in the element,
C_c	= compression index
Cs	= swelling index,
σ_v	= vertical total stress,
$\Delta\sigma_v$	= change in the total vertical stresses,
u_{wf}	= final pore water pressure,
$(u_a$-$u_w)_e$	= matric suction equivalent
θ_s	= saturated water content,
θ_r	= residual water content,
ψ	= suction head (cm),
n,m,α	= empirical shape fitting parameters.
K	= unsaturated hydraulic conductivity
K_s	= saturated hydraulic conductivity
l	= soil specific parameter generally assumed to be 0.5.

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MATHEMATICAL FORMULATION

The most important concepts in the study of soil consolidation process is the Terzaghi's principle of effective stress. The total stress given by force per unit area is represented by the weight of the overlying soil and water and the externally applied load if any. The upward force balancing this stress is represented by the pore pressure and the effective stress.

But according to Fredlund and Hung [4] stated that the volume change constitutive relations for the unsaturated soils are formulated using the two stress state variables namely; net normal stress and matric suction, thus a modification of Terzaghi''s principle of effective stress of unsaturated soils is given by equation (1),

$$\sigma' = \sigma - u_a - \chi(u_a - u_w) \tag{1}$$

The above equation is known as the modified Terzaghi's principle of effective stress for unsaturated soils. As the soil particles are assumed to be largely incompressible, any deformation in the soil matrix is essentially due to changes in the pore volume. The equation (1) implies that change in effective stress state of the soil is determined by the behavior of the pore pressure. And any change in pore pressure is reflected into changes in effective stress provided that there is no change in total stress.

It is assumed no external load applied, that may cause expulsion of air and consolidation, emphasis is on root water-uptake as it relates effective stress. It is also assumed that the pore-air pressure is the same with atmospheric pressure; this means the distribution of pore-water pressure is equivalent to the matric suction distributions Fredlund and Hung [4].

$$\sigma' = \sigma - u_w \tag{2}$$

The pore water pressure will be negative quantity in an unsaturated soil and the negative pore water pressure, when expressed in an equivalent head of water is taken to mean the same thing as capillary potential *(ψ)*,

$$u_w = -\frac{u_w}{\gamma_w} = -\frac{\gamma_w h}{\gamma_w} = \psi = -h \tag{3}$$

Therefore equation (2) becomes,

$$\sigma' = \sigma - \psi \tag{4}$$

The continuity principal applied to the flow in two directions in a referential element yields the two-dimensional axi-symmetric domain,

$$\left(\frac{V_r}{r} + \frac{\partial V_r}{\partial r} + \frac{\partial V_z}{\partial z}\right)V_T = \frac{\partial V_w}{\partial t} \tag{5}$$

For a constant volume and expressing equation (5) employing Darcy's Law expressed for flow in an unsaturated soils. The total potential for the moisture flow taken as the sum of the pressure or capillary potential and the gravitational potential, follows;

$$\frac{\partial \theta}{\partial \psi}\cdot\frac{\partial \psi}{\partial t} = \frac{\partial}{\partial z}\left[K(\psi)\frac{\partial \psi}{\partial z}\right] + \frac{1}{r}K\frac{\partial \psi}{\partial r} + \frac{\partial}{\partial r}\left[K(\psi)\frac{\partial \psi}{\partial r}\right] + \frac{\partial K(\psi)}{\partial z} - S(\psi, r, z) \tag{6}$$

The root water-uptake extraction function is the sink term S *(ψ,z,r)* in the equation (6), is given by the equation for water-uptake for two-dimensional axi-symmetric is Rees and Ali [2],

$$S(\psi, z, r) = \frac{4T}{z_r r_r}\alpha(\psi)\left[1 - \frac{z}{z_r}\right]\left[1 - \frac{r}{r_r}\right] \tag{7}$$

The numerical solution of equation (6) via the finite element spatial discretization procedure and a finite-difference time-stepping scheme particular adopting a Galerkin weighted residual approach which will yield the disctretized matrix form with added deformation component for full detail see Rees and Ali [2].

$$\boldsymbol{K}\boldsymbol{\psi}_s + \boldsymbol{C}\frac{\boldsymbol{\psi}_s}{\partial t} + \boldsymbol{J} + \boldsymbol{S} = 0 \tag{8}$$

The parabolic shape functions and eight-node isoperimetric elements are employed Zienkiewicz and Taylor [5]. The time-dependent nature of equation (8) is dealt with via a mid-interval backward difference technique, yielding

$$\underline{K}^{n+1/2}\underline{\psi}^{n+1} + \underline{C}^{n+1/2}\left[\frac{\underline{\psi}^{n+1} - \underline{\psi}^{n}}{\Delta t}\right] + \underline{J}^{n+1/2} + \underline{S}^{n+1/2} = 0 \tag{9}$$

The capillary potential (*ψ)* was estimated from equation (6) which was used as an input for the stress-deformation analysis. This relationship was established to perform the necessary deformation estimation,

$$\frac{\partial \varepsilon}{\partial \psi} = \frac{1}{V_T}\frac{\partial V_v}{\partial t} = \frac{1}{H_T}\frac{\partial V_v}{\partial \psi} \tag{10}$$

For a laterally confined soil, the change in volume is proportional to the change in soil matrix thickness and the initial volume is proportional to the initial thickness.

The elasticity parameters are functions of the stress state of the soil, net normal stress and the matric suction. The elasticity parameters could be estimated using equation from Fredlund and Rihardjo [6] they were coded into FORTRAN code.

While the soil is a normally consolidated clay with a consolidation behaviour that can be described by,

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$$de = C_c \ln\left(\frac{\sigma_v + \Delta\sigma_v - u_{wf}}{(\sigma_v - u_a) + (u_a - u_w)_e}\right) \quad (11)$$

The boundary condition for the stress-deformation analysis involved having the soil free to move in the vertical direction and fixed in horizontal direction at the left and right sides of the domain and the lower boundary would be fixed in both directions.

MATERIALS AND METHODS

The required soil moisture retention characteristics and unsaturated hydraulic conductivity would be simulated from the closed form equation developed by vanGenuchten [7] thus;

$$\theta(\psi) = \theta_r + \frac{(\theta_s - \theta_r)}{\left[1 + |\alpha\psi|^n\right]^m} \quad \begin{matrix}\psi \geq 0 \\ \psi < 0\end{matrix} \quad (12)$$

$$K = Ks\frac{\left[\left(1 + |\alpha\psi|^n\right)^m - |\alpha\psi|^{n-1}\right]^2}{\left(1 + |\alpha\psi|^n\right)^{m(l+2)}} \quad (13)$$

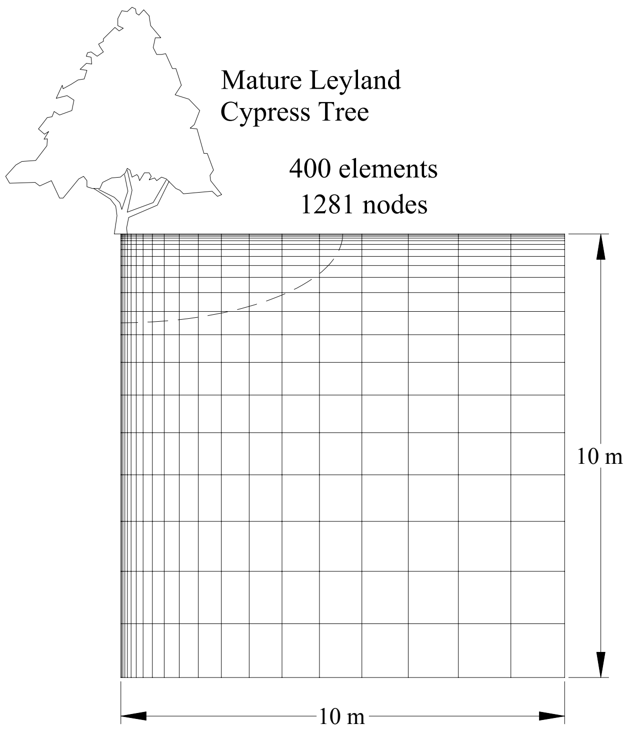

Figure-1. Finite element mesh.

The model mesh consists of 8-noded isoperimetric linear strain quadrilateral elements. The entire mesh Finite Element mesh consists of 1281 nodes and 400 elements. (Figure-1) The mesh was configured to offer some refinement within the root zone area since this is the region where the most significant moisture content variations were expected to occur. The simulation employs a time-step size of 21 600 seconds, which was held constant for the entire period considered. A mature 10m in height, Leyland Cypress tree 10m height located on Gault clay sub-soil at Corpus Christi College, Cambridge, England considered for this analysis. The soil parameters are shown in Table-1.

Table-1. Parameters used in the analysis.

Parameters	Values	Reference
k_s	10^{-6}m/s	Biddle [1]
T_p	5mm/day	Biddle [1]
ψ_d	1500kPa	Feddes *et al.* [8]
γ	20kN/m^3	Indraratna *et al.* [9]
e_0	1.25	Samuels [10]
C_s	0.023	Ng [11]
μ	0.30	Almeida *et al.* [12]
θ_r	0.12	Rees and Ali [2]
θ_s	0.55	Rees and Ali [2]
α	0.560	Rees and Ali [2]
m	0.29	Rees and Ali [2]
n	1.4	Rees and Ali [2]
l	0.5	Rees and Ali [2]

MODEL VERIFICATION

The numerical results seem to agree with Fredlund and Hung [4] analysis, the difference is about 5% to 6%, see Ali and Mu'azu [13]. The slight disparity between the results is two entirely different unsaturated soil models are used in his study. These are the stress state variable for unsaturated soil with Bishop's effective stress theory for the unsaturated coded using FORTRAN and Fredlund and Hung [4] strictly stress state variable for unsaturated soils. The two different theories influence the volume of change of an unsaturated soil differently. This verification exercise confirms that if the relevant parameters are known, then the current finite element model can predict the matric suction generated and the ground deformation caused by vegetative induced moisture movement. The water uptakes are validated with Biddle [1] and see Rees and Ali [2].

RESULTS AND DISCUSSIONS

The results show decrease in ground movement as the distance from the trunk increases outwards. Figures 2, 4 and 6 show the matric suction changes at various positions of Leyland Cypress tree away from the trunk of the tree considering the rainfall effects for 30, 190 and 270 days, respectively. The matric suction decreases as the distance increases away from the tree trunk.

The magnitude of volume change as a result of vegetative moisture uptake depends much on, not only on the rate of transpiration but also to a greater extends on the soil types and its properties such as degree of compressibility shrinkage and swelling indices. The vegetative induced ground movement might be as a result of vegetative moisture induced migration which causes change in strain resulting from an increased in matric suction. This partly attributed to root water-uptake which causes changes in volume of void and porosity.

The graph show recharge as a result of rainfall effects as can be seen in Figures 4, 6 and 8. The effect of rainfall was included; rainfall data provided by the Meteorological Office [14] has been acquired for the nearest weather station to the site (Wolverton Hampshire) which incorporated into the FORTRAN code.

The results show decrease in ground movement as the distance from the trunk increases outwards. Figures 3, 5 and 7 show the ground deformation changes at various positions of Leyland Cypress tree away from the trunk of the tree considering the rainfall effects for 30, 190 and 270 days, respectively. The ground movement decreases as the distance increases away from the tree trunk. The graph show recharge as a result of rainfall effects as can be seen in Figures 5 and 7. The graphs shows negative values of ground deformation as a result ground swelling due to water flux boundary condition at 7.5m and 10.0m away from the tree trunk.

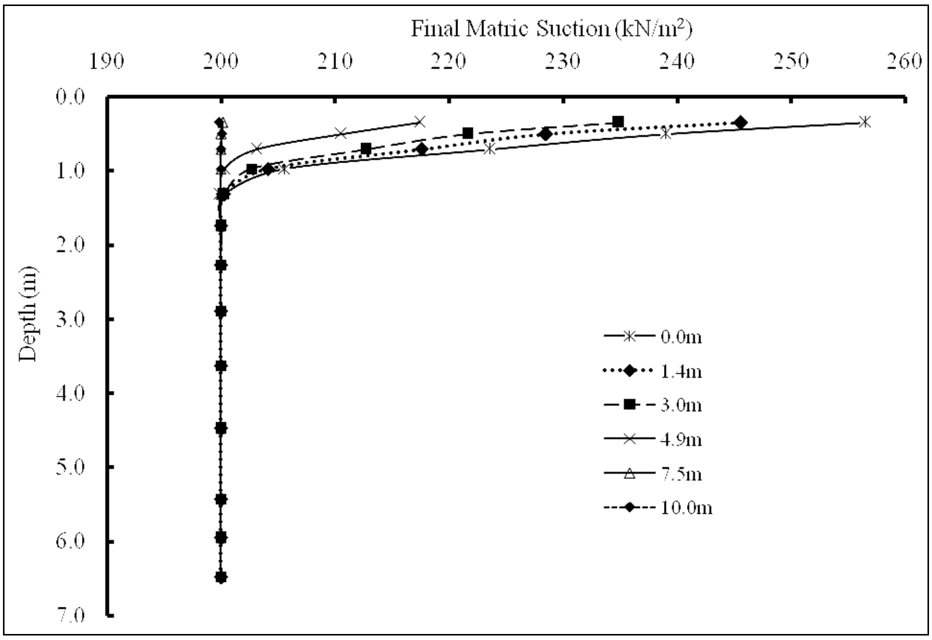

Figure-2. Variations of matric suction with depth at various distance from the cypress tree after 30 days with rainfall.

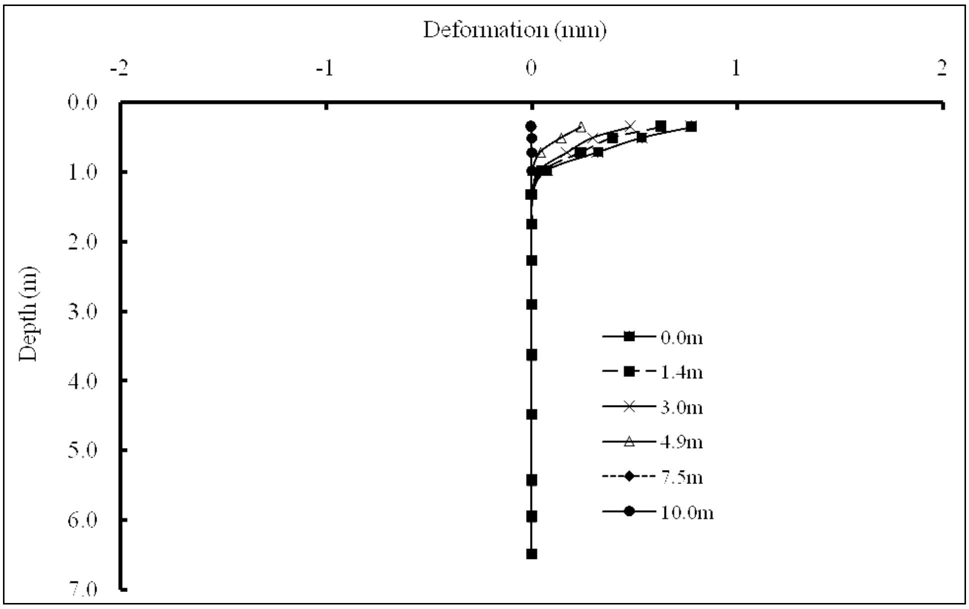

Figure-3. Ground settlement with depth at various distance from the cypress tree after 30days with rainfall.

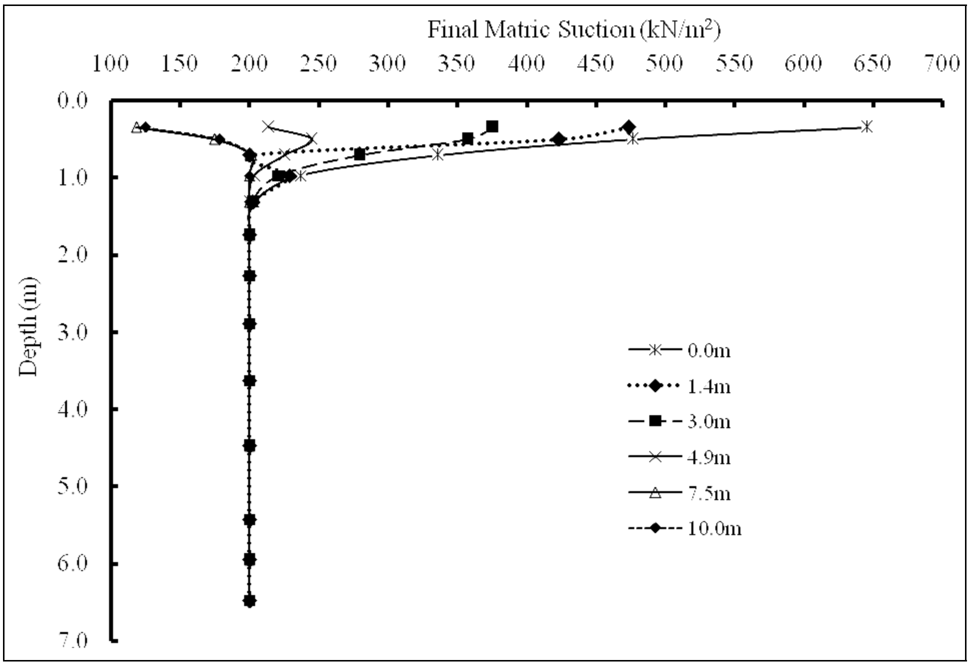

Figure-4. Variations of matric suction with depth at various distance from the cypress tree after 190 days with rainfall.

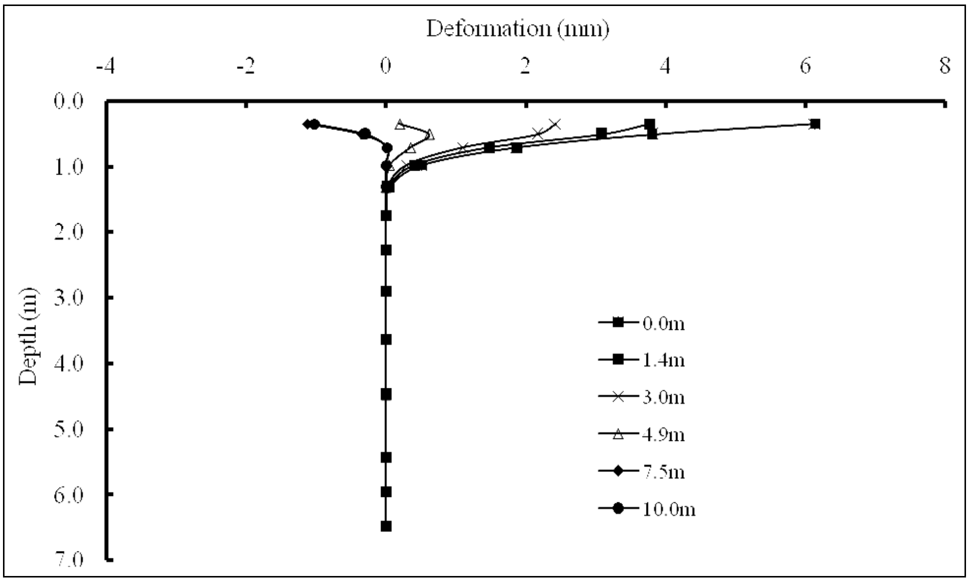

Figure-5. Ground settlement with depth at various distance from the cypress tree after 190days with rainfall.

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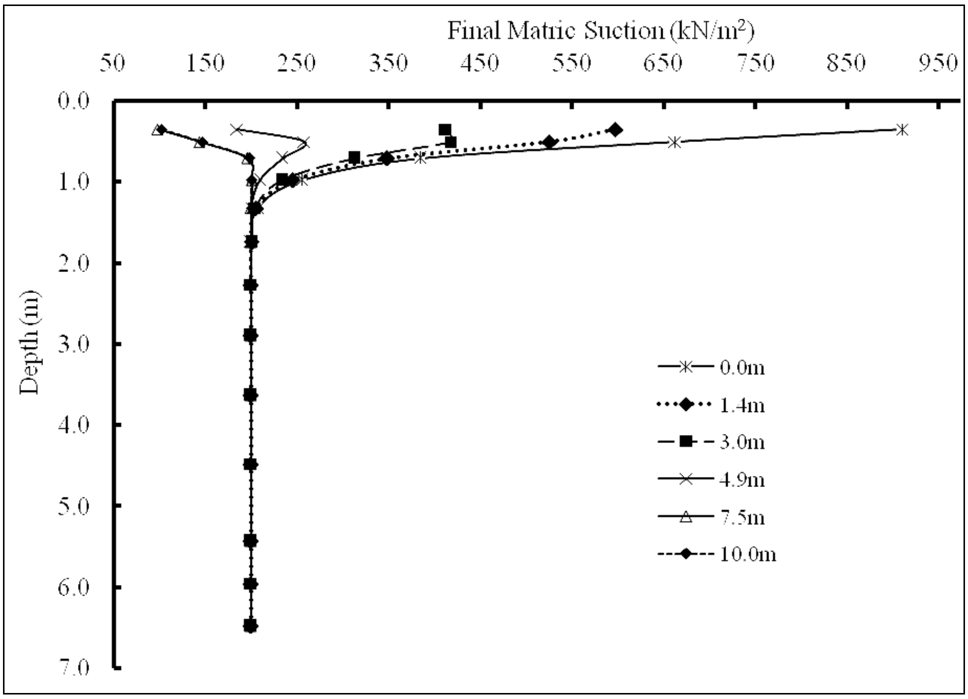

Figure-6. Variations of matric suction with depth at various distance from the cypress tree after 270 days with rainfall.

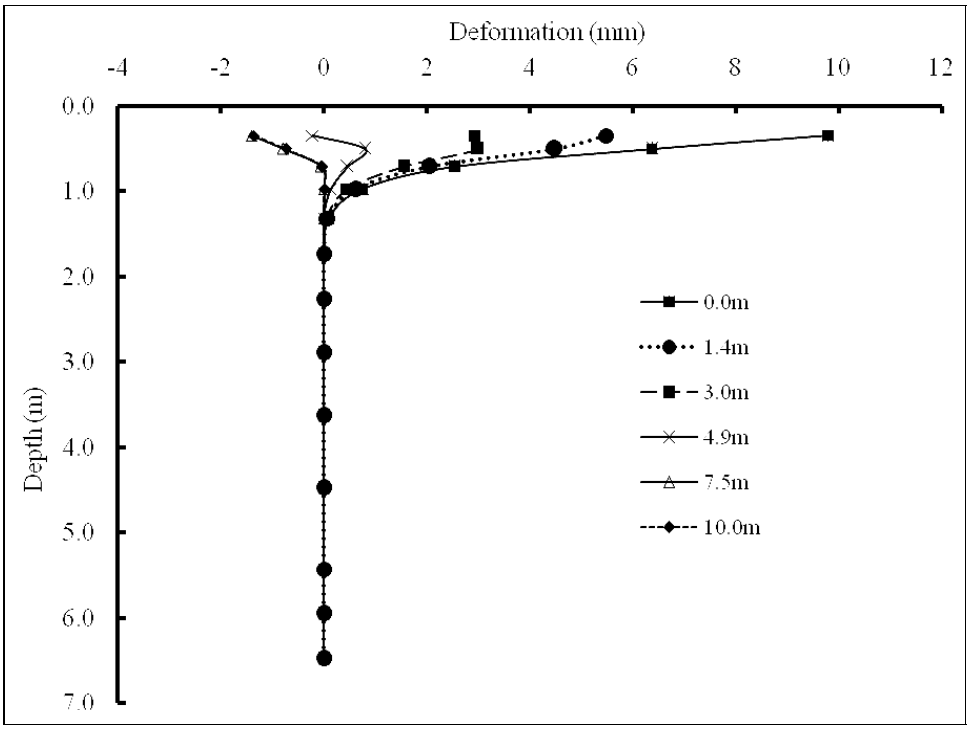

Figure-7. Ground settlement with depth at various distance from the cypress tree after 270days with rainfall.

Figures 8, 10 and 12 show final matric suction for 30, 190 and 270 days, respectively without effect of rainfall. The matric suction decrease as the distance from the trunk Leyland Cypress tree increases, and invariable the deformation also decreased as lateral distance increases farther away from the tree.

The results show decrease in ground movement as the distance from the trunk increases outwards. Figures 9, 11 and 13 show the ground deformation changes at various positions of Leyland Cypress tree away from the trunk of the tree considering without the rainfall effects for 30, 190 and 270 days, respectively. The ground movement

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decreases as the distance increases away from the tree trunk. The graphs show no recharge because no rainfall effects as can be seen in Figures 9, 11 and 13. The graphs do not shows negative values of ground deformation so there is no any ground swelling due to water flux boundary condition at 7.5m and 10.0m away from the tree trunk.

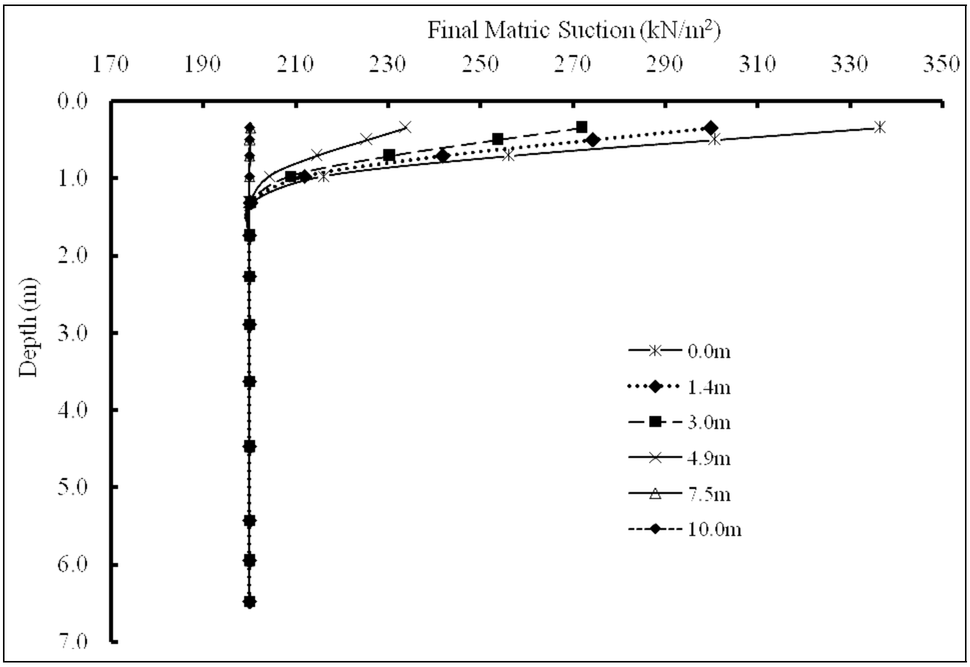

Figure-8. Variations of matric suction with depth at various distance from the cypress tree after 30 days without rainfall.

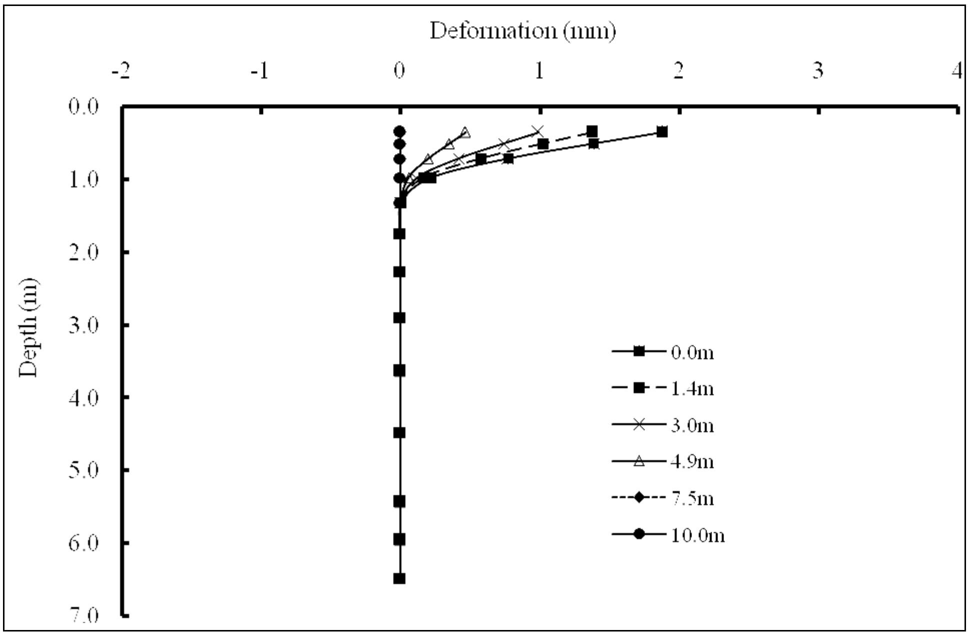

Figure-9. Ground settlement with depth at various distance from the cypress tree after 30days without rainfall.

The ground movement changes at various distances away from Cypress tree trunk. The ground settlement that is induced by root water-uptake consolidates the soil and decreases with depth. The ground settlement is caused by both the root water uptake and the evaporation from the soil surface. The rest of the settlement is assumed to be induced by transpiration. Soil matric suction induced by tree root water uptake propagates radially. The full cycle simulation of matric suction and deformation provides valuable information on

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how rainfall effects affect both matric suction and ground movement changes.

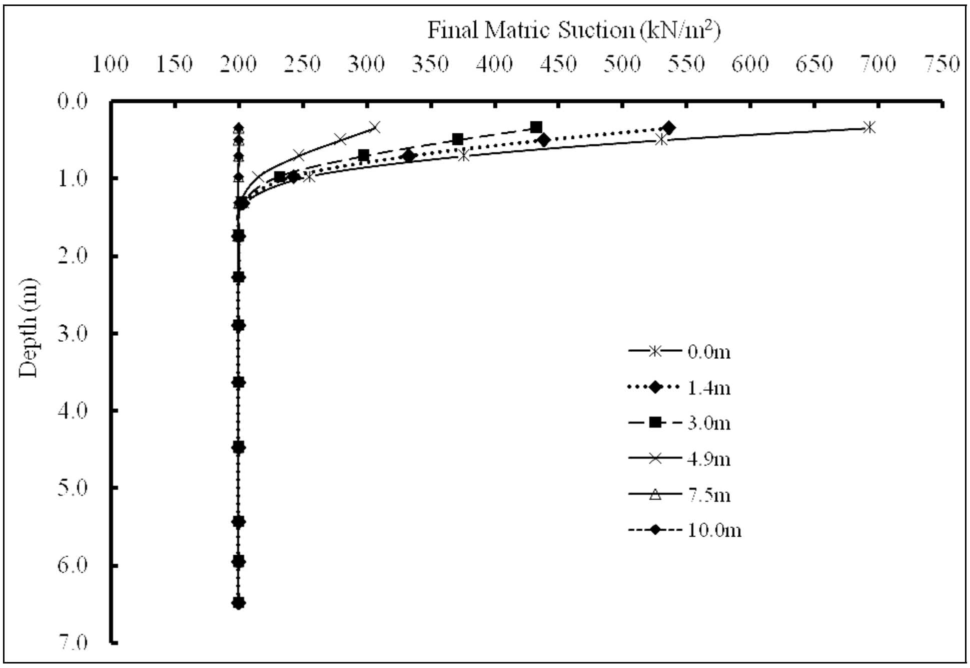

Figure-10. Variations of matric suction with depth at various distance from the cypress tree after 190 days without rainfall.

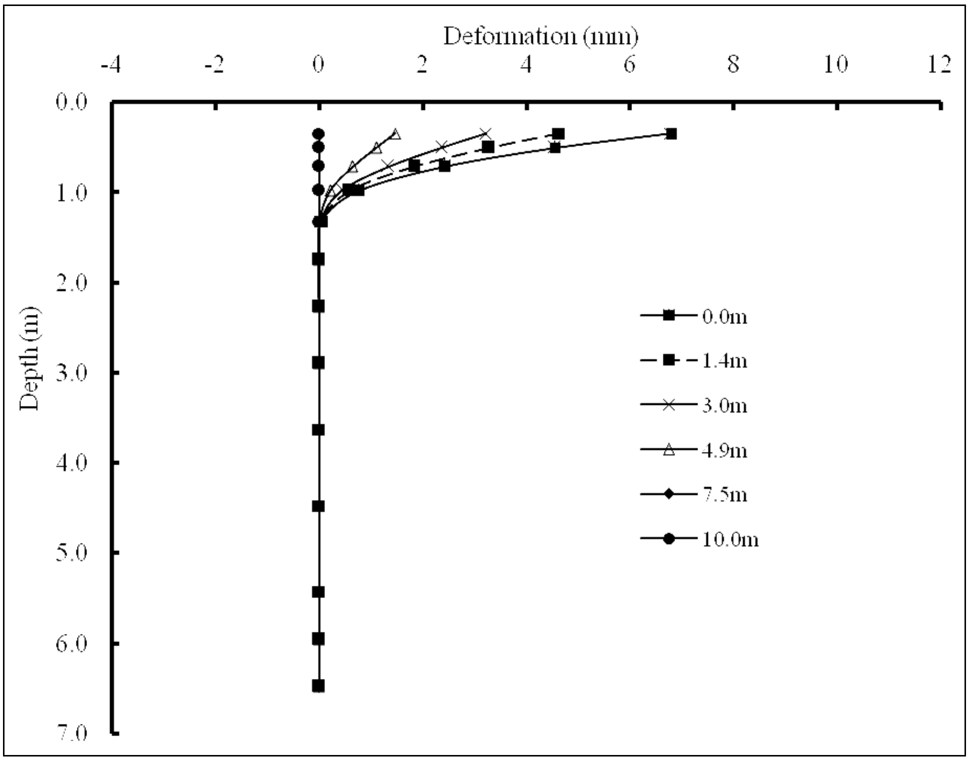

Figure-11. Ground settlement with depth at various distance from the cypress tree after 190 days without rainfall.

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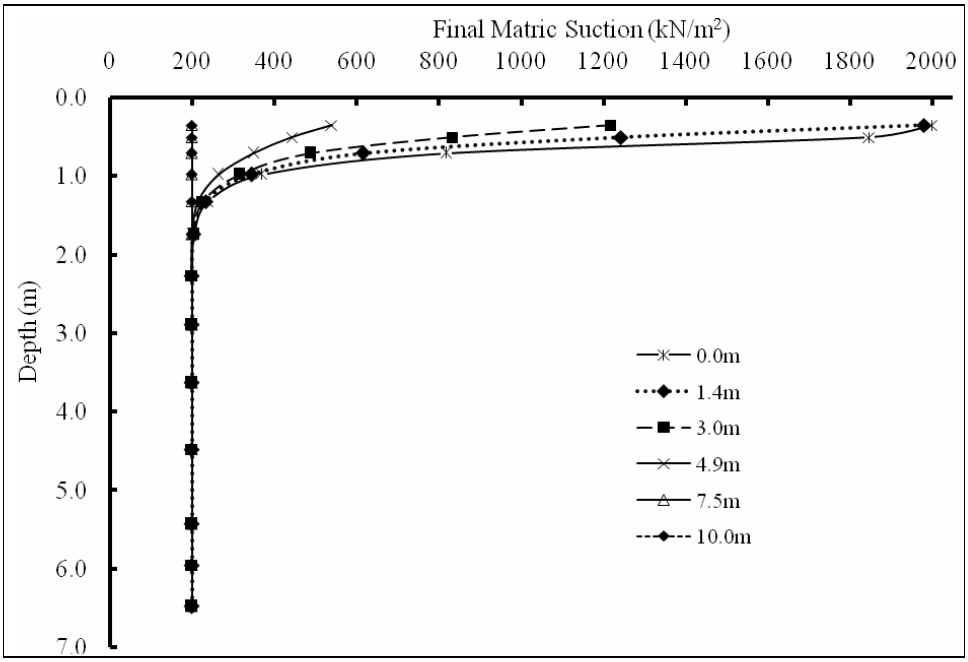

Figure-12. Variations of matric suction with depth at various distance from the cypress tree after 270 days without rainfall.

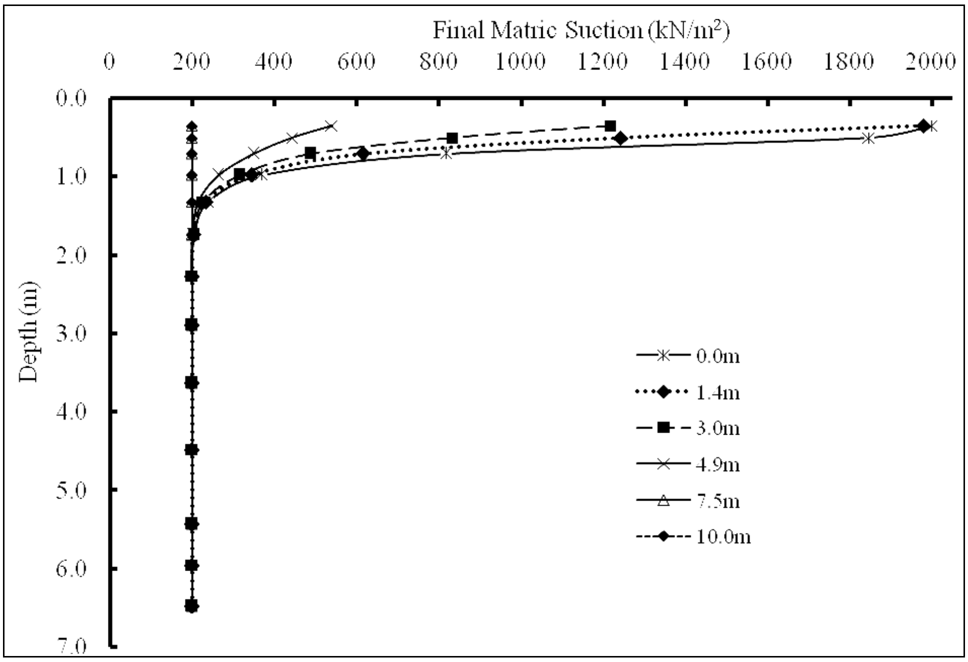

Figure-13. Ground settlement with depth at various distance from the cypress tree after 270 days without rainfall.

CONCLUSIONS

The model is capable of predicting soil moisture content and matric suction distributions in the vicinity of vegetation considering various atmospheric condition, plant specifications, and ground conditions. The effect of with and without rainfall has been incorporated into the simulation work. The full cycle simulation of matric suction and deformation provides valuable information on how effect of rainfall affects both matric suction and ground movement changes. Generally rainfall reduces the amount of the root generated matric suction and ground movement due to recharge. The matric suction and ground movement changes with and without rainfall effects likely to provide practicing geotechnical engineers an effective tool on decision making as regard to full cycle effect of with and without rainfall for designing structures on vadose zones containing vegetation.

REFERENCES

[1] Biddle P. G. 1998. Tree Root Damage to Buildings. Willowmead Publishing Ltd., Wantage.

[2] Rees S.W., Ali N. 2006. Seasonal water uptake near trees-a numerical and experimental study. Geomech. Geoeng. 1(2): 129-138.

[3] Carslaw H.S. and Jaeger J.C. 1959. Conduction of heat in solids. Oxford University Press, Oxford.

[4] Fredlund D.G. and Hung V.Q. 2001. Predictive of volume change in an expensive soil as a result of vegetation and environmental changes. In: Vipulanandan, Addison, Hasan (Eds) Expansive Clay Soils and Vegetative Influence on Shallow Foundations. Geo Institute, ASCE. pp. 24-43.

[5] Zienkiwicz O.C. and Taylor R.L. 1989. The Finite Element Method. McGraw-Hill, USA.

[6] Fredlund D.G. and Rihardjo H. 1993. Soil Mechanics for Unsaturated Soil. John Wiley and Sons, New York. pp. 346-373.

[7] VanGenuchten MTh. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44: 892-898.

[8] Feddes R. A., P. Kowalik K. K. Malinka and H. Zaradny. 1976. Simulation of field water uptake by plants using a soil water dependent root extraction function. Journal of Hydrology. 31: 13-26.

[9] Indraratna B., Fatahi B. and Khabbaz H. 2006. Numerical analysis of matric suction effects of the roots. Geotech. Eng. 159: 77-90.

[10] Samuels S.G. 1975. Some properties of the Gault Clay from Ely-Ouse Essex water tunnel. Geo technique. 25(2): 239-264.

[11] Ng C.W.W. 1998. Observed performance of multi-propped excavation in stiff clay. J. Geo. env. 124(9): 889-906.

[12] Almeida M.S.S., Britto A.M. and Perry R.H.G. 1986. Numerical modeling of a centrifuged embankment on soft clay. Canadian Geotechnical Journal. 23(20): 103-114.

[13] Ali N. and Mu’azu M.A. 2010. Simulation of Vegetative Induced Deformation in an Unsaturated Soil. American Journal of Environmental Science. 6(2):130-136.

[14] Bureau of Metrology. 2006. United Kingdom Bureau of Metrology. Meteorological Rainfall Data (1979-1980). Meteorological Office, Exeter, United Kingdom.

APPENDIX-I

$$\boldsymbol{K}=\sum_{e=1}^{m}\int_{\Omega^e} r\left[K\frac{\partial N_s}{\partial r}\cdot\frac{\partial N_r}{\partial r}+K\frac{\partial N_s}{\partial z}\cdot\frac{\partial N_r}{\partial z}\right]\partial\Omega^e$$

$$\boldsymbol{C}=\sum_{e=1}^{m}\int_{\Omega^e} r\left[N_r N_s C\right]\partial\Omega^e$$

$$\boldsymbol{J}=\sum_{e=1}^{m}\int_{\Omega^e} r\left[N_r\frac{\partial K}{\partial z}\right]\partial\Omega^e-\sum_{e=1}^{m}\int_{\Gamma^e} r\left[N_r\lambda\right]\partial\Gamma^e$$

$$\boldsymbol{S}=\sum_{e=1}^{m}\int_{\Omega^e} r\left[N_r S(r,z)\right]\partial\Omega^e$$