

Modelling the impact of depth distributed plant water uptake on Soil-Plant-Atmosphere Interactions

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Abstract. The soil-plant-atmosphere interaction (SPAI) significantly influences the safety and serviceability of engineering infrastructure by affecting pore water pressure (PWP) distribution. Rainfall and water infiltration increase PWPs, reducing soil strength, while evapotranspiration—driven by evaporation and plant transpiration—induces negative pore pressures (suction), enhancing soil strength and safety. However, vegetation can also pose serviceability challenges. During summer, root water uptake causes soil shrinkage, and in wet months, infiltration induces swelling. These cyclic volume changes can disrupt infrastructure, leading to road and track delays or closures. Accurate modelling of SPAI is therefore critical to understanding the effects of climate change and vegetation on soil hydraulic and mechanical behaviour. This study examines how surface and internal flow boundary conditions affect SPAI modelling within a fully coupled flow-deformation framework. While most recent research has focused on surface boundary conditions for hydrological fluxes, this paper evaluates the inclusion of internal boundary conditions to simulate vegetation transpiration. A comparative analysis assesses the safety and serviceability outcomes for models employing only surface boundary conditions versus those incorporating both surface and internal conditions.

1 Introduction

Pore Water Pressures (PWP) and its changes are critical factors influencing the soil's effective strength and its cyclic volume change [1]. Various approaches have been attempted to model Soil-Plant-Atmosphere Interaction (SPAI) from using a seasonal undrained shear strength profile for London Clay [2], seasonal PWP profiles [3, 4] and running non-coupled analysis to calculate PWPs separately to then implement in a slope stability analysis [5]. More recently, fully coupled flow-deformation analysis have been used where hydrological fluxes have been applied as an infiltration surface boundary condition (BCs) [1, 6].

This paper discusses how the placement of BCs affects cut slopes. A typical UK cut slope was considered and assumed to be covered by a deciduous forest. The hydrological fluxes parameters were calculated using an ecohydrological model (T&C) to represent SPAI [7, 8]. The parameters were then implemented in a Finite Element geotechnical model (PLAXIS 2D) using infiltration BCs [9]. In this paper, this methodology is compared with an alternative approach where transpiration is applied at depths within the root zone, using outflow BCs in PLAXIS 2D. The vertical displacement against time and the normalized maximum differential displacement against the

considered distance from both analyses were compared and its effect on the cut slope's serviceability was investigated.

2 Problem Definition

The cut slope considered in this study has a height of 8 m and a width of 28 m and it is assumed to be covered by deciduous trees having a root depth of 2 m. To simulate SPAI, an ecohydrological model (T&C) was integrated with Finite Element geotechnical software (PLAXIS 2D). two approaches were used to model the vegetation cover and its transpiration: A) Surface BC: a single infiltration surface BC was applied to account for all hydrological fluxes, and B) Combined surface and internal BC: the infiltration surface BC is used for all hydrological fluxes excluding transpiration and the internal outflow BCs at various depths within the root zone to represent transpiration separately. The purpose of these analyses is to evaluate the impact of incorporating internal BCs for vegetation modelling, offering a more detailed representation of the plant water uptake processes and its influence on slope behaviour.

For this analysis, a stratigraphy of 72.5 m has been selected, consisting of 3 m of weathered London Clay (WLC), 46 m of intact London Clay (ILC) and 23.5 m of

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Lambeth Group Clay (LGC). The lower boundary is aligned with the upper chalk layer [10]. It is assumed that the vegetation is a deciduous tree forest with roots extending to a depth of 2 m. The hydraulic conductivities for WLC, ILC and LGC were set to 3.715×10^{-3} , 3.715×10^{-4} and 3.715×10^{-4} m/day, respectively. While ILC and LGC are considered to be fully saturated, WLC is modelled to desaturate according to the Van-Genuchten Soil Water Retention Curve (SWRC) based on field data from Smethurst et al. [11]. The parameters used for the SWRC are $m = 1/3$, $n = 1.5$ and $\alpha = 0.15$ 1/m, with a residual degree of saturation of 0 and a saturated degree of saturation of 1. The cut slope excavation was done in 1997, and the analysis covers the period from July 1997 till December 2008 [11].

3 Methods Section

3.1 Ecohydrological Model (T&C)

The Tethys-Chloris ecohydrological model (T&C) is a mechanistic, physics based model developed to simulate coupled water, energy, and carbon budgets at land surface in an hourly time scale [7, 8]. T&C accounts for water movement into and out of the soil, including precipitation, infiltration to soil, evaporation from bare ground and snow, intercepted evaporation, transpiration and run-off.

T&C calculates an internal parameter called “Fraction of fine roots in soil layers”, which defines a flexible distribution of fine roots within the soil. This parameter represents the percentage of active water-absorbing fine roots present at different depths within the soil. The root distribution was assumed to decline exponentially with depth, as showed in Fig. 1 as Root fraction 1. Most of the root density is present in the upper part of the root zone depth [12]. Using this parameter, the transpiration at different depths can be calculated and implemented using internal BCs.

3.2 Geotechnical Model (PLAXIS 2D)

The analysis was carried out using a 2D-plane-strain model in PLAXIS 2D. Fig. 2 shows the modelled cut slope in PLAXIS 2D. The soil layers were modelled using a Mohr-Coulomb failure criterion, incorporating isotropic small strain stiffness [13], [14], [15] and the User Defined Soil Model (UDSM) properties are presented in Table 1 [1, 4]. A non-linear anisotropic permeability variation with mean effective stress was applied to all soil layers [16].

$$k_v = k_{y,\text{ref}} e^{ap'} \quad (1)$$

where $k_{y,\text{ref}}$ is the reference permeability along the y direction, k_v is the current vertical permeability, p' is the mean effective stress [kPa] and a is a dimensionless fitting parameter set to 0.007 [17]. A horizontal to vertical permeability ratio of 10 was applied [18].

The coefficient of earth pressure at rest (K_0) values were set to 1.2 for WLC, 1.5 for ILC and 1.0 for LGC.

The excavation was simulated in three undrained phases. For analysis A, the net infiltration which is calculated as the difference between precipitation and evaporation from bare ground and snow, intercepted evaporation and transpiration, was applied as a surface boundary condition in PLAXIS 2D using the infiltration BC. This infiltration boundary condition is a dual boundary condition that can switch from prescribed pore water heads to an inflow/outflow infiltration rate, with the maximum allowable head set to -0.5 m and the minimum set to -100 m [19]. For analysis B, all hydrological fluxes except transpiration (infiltration, evaporation from bare ground and snow and intercepted evaporation) were applied at the surface of the soil using an infiltration BC; However, transpiration was partitioned following the fine root distribution, thorough internal outflow boundary conditions in PLAXIS 2D. Multiple internal boundary conditions were defined parallel to the surface of the soil and transpiration for each boundary condition was calculated using the root fraction function shown in Fig. 1. Here, the root zone was divided into five sections and five internal boundary conditions were implemented at different depths (with the boundary conditions being closer to one another near the slope surface where the max roots are present and further spaced out deeper in the soil where less percentage of roots are present). The right hand side boundary condition and the left hand side, which was the axis of symmetry, was set to impermeable. The bottom boundary condition that coincides with chalk was set to seepage to allow free water movement.

4 Analysis Results (Serviceability)

The vertical displacement of a node at mid slope at surface and 0.5 m in depth against time (Fig. 3) shows a slight increase in analysis B, since transpiration is applied within the root zone which contributes to the soil's shrinking and swelling. Nonetheless, the maximum differential displacement at the bottom of the excavation, which is key for serviceability, remains nearly the same for these two analyses. This is seen in Fig. 4 which plots vertical displacement with distance from the toe of the cut slope to the excavation center line at the instance with the maximum difference in suction. This indicates that modelling internal BCs has a minimal impact on slope serviceability.

To put the differential displacements calculated into perspective, Network Rail has set the cross level maintenance tolerance in the UK to 10 mm [20], which for a 1,435 mm track gauge, corresponds to a normalized ratio of 6.97 (10 mm over 1.435 m). The calculated normalized ratio, i.e. the ratio of the maximum difference in vertical displacement [mm] over excavation centreline distance to the cut slope's toe [m], for the instances with the maximum difference in suction (Fig. 5), are below this threshold, with negligible differences between each ratio [21].

5 Discussions

As mentioned in the previous section, slope's behaviour when modelling with only surface boundary condition and when including internal boundary conditions did not change significantly. This could be due to the fact that the maximum root fraction (as shown in Fig. 1), is present near the surface, meaning that most of the transpiration will also be applied close to the surface; hence both approaches will have similar results. So, in order to inspect the effect of applying max transpiration a bit deeper in the root zone area, a new user defined root fraction was defined, as shown in Fig. 1 as Root fraction 2. After re-running both analyses and plotting the vertical displacement at the bottom of the excavation against distance from the excavation centreline (in Fig. 6), it can be seen, compared to the results from the previous section (shown in Figs. 3 to 5), the changes in vertical displacement closer to the toe of the slope is now more visible, with analysis B showing larger heave close to the toe of the slope; although the difference in both vertical displacement and max differential displacement are still small.

6 Conclusions

The effect of two approaches to modelling vegetation's hydraulic influence, i.e. transpiration is investigated in this paper: A) applying all hydraulic fluxes, including transpiration as a surface BC and B) applying all hydraulic fluxes, excluding transpiration at the soil surface, and applying transpiration at different depths within the root zone, using internal BCs. The results show that internal BCs have a minor impact on the infrastructure's serviceability, with no significant difference in vertical displacement. This indicates that modelling vegetation with only a single surface BC can capture the necessary aspects regarding serviceability. The max transpiration for this type of tree, occurs in the top 0.5 m of the soil. It is also shown that when maximum transpiration happens in deeper depths, the differences become more visible compared to the previous set of analysis. But these results are for a typical UK tree cover and weather data. It is speculated that if a plant has much deeper roots, so that the maximum transpiration occurs in deeper depths, the difference between these two modelling approaches could be more visible.

Table 1. Mechanical properties for all three soil layers.

User Defined Soil Model parameters		Values
G_{ref} [kN/m ²]	Reference shear modulus	955
K_{ref} [kN/m ²]	Reference bulk modulus	1665

p_{ref} [kN/m ²]	Reference pressure	1
m_g [-]	Nonlinearity of stress dependency of shear modulus	0.7
m_k [-]	Nonlinearity of stress dependency of bulk modulus	0.7
a_0 [-]	Basic degradation parameter for G_{tan}	0.181×10^{-3}
b [-]	Nonlinearity degradation of G_{tan}	1.3
RG_{min} [-]	Normalized degradation limit for G_{tan}	0.05
G_{min} [kN/m ²]	Minimum shear stiffness	2000
r_0 [-]	Basic degradation parameter for K_{tan}	0.3×10^{-3}
s [-]	Nonlinearity degradation of K_{tan}	1.1
RK_{min} [-]	degradation limit for K_{tan}	0.079
K_{min} [kN/m ²]	Minimum bulk stiffness	3000
φ [°]	Angle of shearing resistance	23
c [kN/m ²]	Cohesion	7
ψ [°]	Dilatancy angle	0

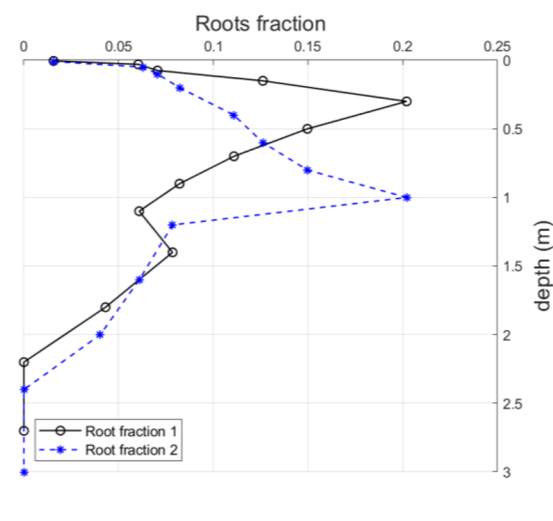


Fig. 1. Root fraction changes against depth for the root zone depth.

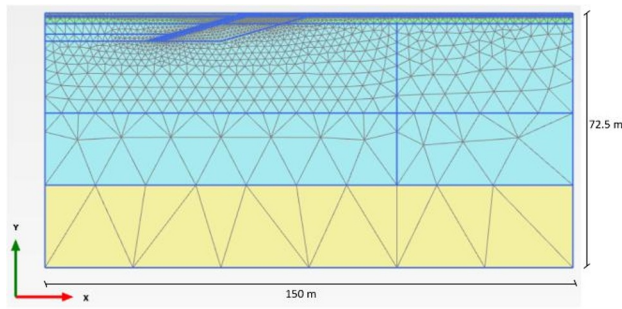


Fig. 2. 2D model of the cut slope before excavation and its meshing.

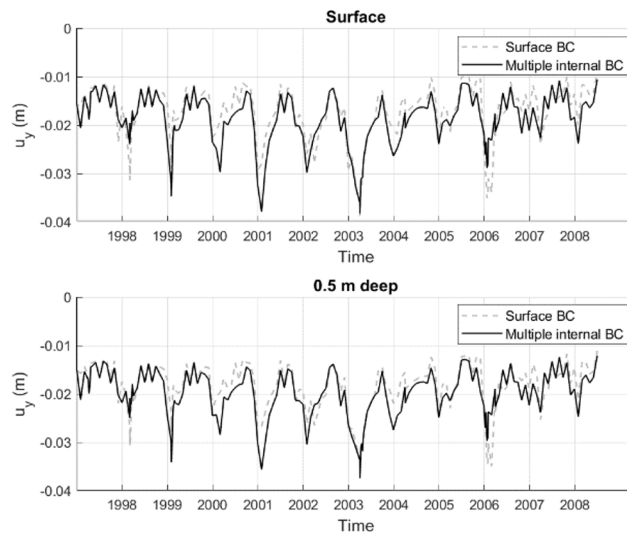


Fig. 3. Time series of vertical displacement at surface and 0.5 m in depth for the two analyses.

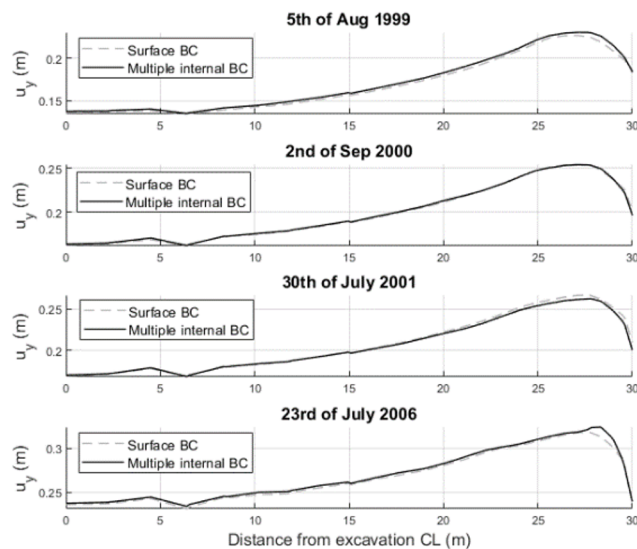


Fig. 4. Cross section of vertical displacement against distance from the excavation centreline to the cut slope's toe (i.e. $x = 0$ is the excavation centreline).

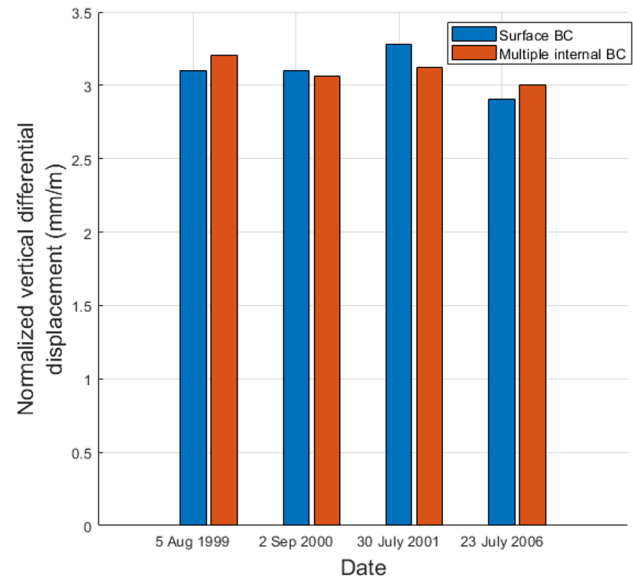


Fig. 5. Normalized ratio of the vertical displacement (at instances with max difference in suction for the two analyses).

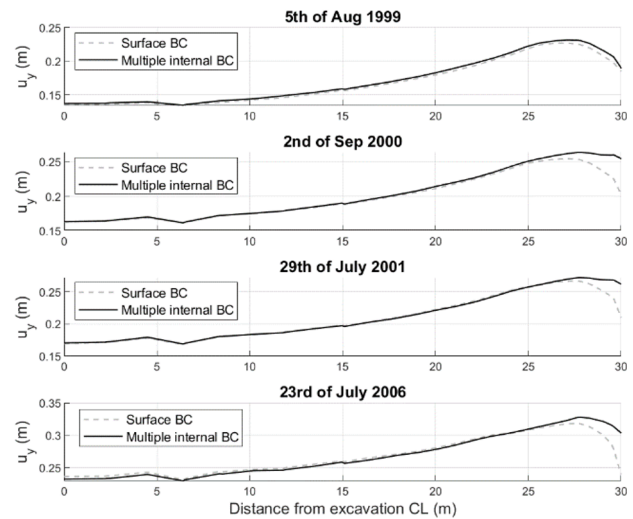


Fig. 6. Cross section of vertical displacement against distance from the excavation centreline to the cut slope's toe for the user defined root fraction 2).

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