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IMPACT OF DEPTH DISTRIBUTED PLANT WATER UPTAKE ON SLOPE SAFETY

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Thousands of cut slopes in the UK, support the country's infrastructure. Pore Water Pressure (pwp) and suction can affect the stability of geotechnical infrastructures. Rainfall reduces suction and increases pwp, decreasing soil shear strength and stability. Near surface pwps are significantly influenced by environmental conditions and vegetation. High water demand from trees with extensive root zones can generate suctions at great depths through plant water uptake. It is expected that with climate change, average rainfall and intense rainfall events will increase. It is important to predict how suctions and pwps will respond to climate conditions and how vegetation will respond to these changes.Vegetation also causes serviceability issues by cyclic shrinking and swelling of high plasticity clays. It plays a significant role in both safety and serviceability of infrastructures, rendering detailed numerical analysis important. This study shows the importance of soil-plant-atmosphere interaction and its effect on slope safety. By implementing boundary conditions (BC) that account for climate and vegetation changesand its physiological responses, the infrastructure's performance can be studied. For this purpose, a typical cut slope in UK has been chosen. It is assumed that the slope is covered with a deciduous tree forest with 2 m deep roots. In this paper, the placement of BCs and its effect on the infrastructure's safety is discussed. Plant water uptake was considered using the ecohydrological model T&C and is used in a fully coupled flow-deformation analysis in PLAXIS 2D.

Keywords: soil-plant-atmosphere interaction, numerical analysis, vegetation,boundary conditions, safety, transpiration.

1. Introduction

One of the main components affecting cut slopes safety and serviceability is Pore Water Pressures (PWP) and its changes, as it affects the effective stresses within the soil and its cyclic volume change (Tsiampousi et al., 2017). There are different methods of modelling Soil-Plant-Atmosphere Interaction (SPAI), such as adopting a summer and winter undrained shear strength profile for London Clay (Vaughan, 1994), summer and winter PWP profiles (O'Brien et al., 2004), running non-coupled analysis (one to calculate PWPs and one to calculate slope stability) (Rouainia et al., 2009). More recently hydrological fluxes were applied as surface boundary conditions (BC) in a fully coupled flow-deformation analysis (Jamalinia et al., 2019; Tsiampousi et al., 2017; Tsiampousi, 2024).

This paper discusses the impact of BC placement under future climate projections. A typical cut slope in the UK, covered with trees wasassumed. The hydrological fluxes were calculated using an ecohydrological model (T&C) to simulate SPAI(Fatichi, 2021; Fatichi et al., 2012), and were implemented in a Finite Element geotechnical model (PLAXIS 2D) using infiltration BCs(Sequent, 2023). In this paper, this methodology is compared with an analysis where transpiration is applied at root zone depths, using outflow BCs, examiningthe effect of internal BCson the cut slope's safety.

2. Problem Definition

The considered cut slope is 8 m high and 28 m wide and it is assumed to be covered by deciduous trees with 2 m deep roots. SPAI was modelled using an ecohydrological model (T&C) coupled with geotechnical software (PLAXIS 2D). Vegetation's transpiration was modelled in two methods: A) A surface BC including plant's transpiration, and B) surface and multiple internal BCs in the root zone depth to apply the plant's transpiration. The aim is to show the effect of modelling vegetation with internal BCs.

The stratigraphy consists of 72.5 m of soil: 3 m of weathered London Clay (WLC), 46 m of intact London Clay (ILC) and 23.5 m of Lambeth Group Clay (LGC) laying on top of upper chalk (British Geological Survey.). The vegetation cover is assumed to be a deciduous tree forest with 2 m deep roots. The hydraulic conductivity for WLC, ILC and LGC was set to 3.715E-3, 3.715E-4 and 3.715E-4 m/day, respectively. ILC and LGC are assumed to be fully saturated, while WLC is allowed to desaturate following a Van-Genuchten Soil Water Retention Curve (SWRC) based on Smethurst et al. data. The SWRC parameters are m = 1/3, n = 1.5 and ± = 0.15 1/m. The residual and saturateddegree of saturation was 0 and 1, respectively. The cut slope was excavated in 1997 and was initialized until 2008 and subsequently modelled from 2021 to 2040 (Smethurst et al., 2012).

3. Methods

3.1. *Ecohydrological Model (T&C)*

The Tethys-Chloris ecohydrological model (T&C) is a physics based mechanistic model designed to solve coupled water, energy, and carbon budgets at land surface in an hourly time scale. An internal parameter in T&C is “Fraction of fine roots in soil layers”, shown in Fig. 1 (a), allows for flexible root distribution. This parameter enables the calculation of transpiration at different depths and can be implemented using internal BCs.

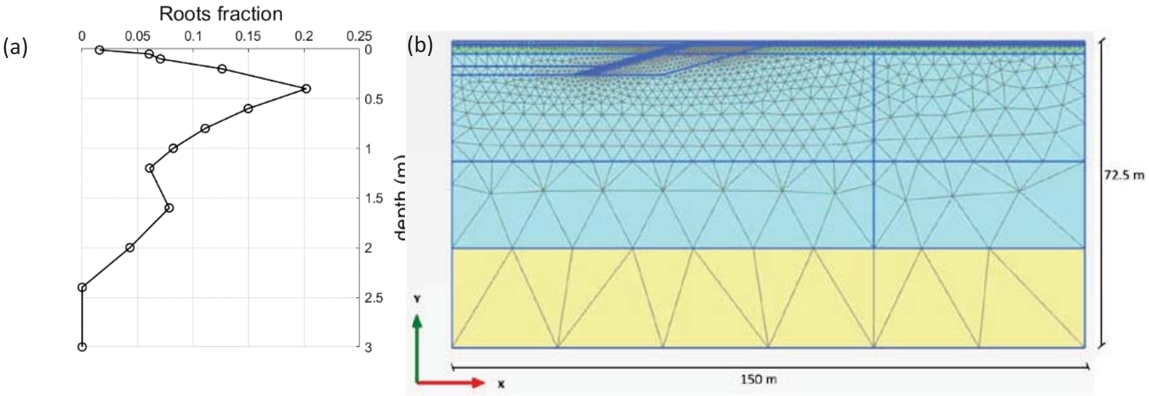

Fig. 1.(a) Root fraction against depth for the root zone, (b) 2D model of the cut slope before excavation and its meshing.

3.2.*Geotechnical Model (PLAXIS 2D)*

The analysis was performed using a 2D-plane-strain model in PLAXIS 2D (Fig. 1(b)). All soil layers were modelled with a Mohr-Coulomb failure criterion with isotropic small strain stiffness (Taborda et al., 2016; Taborda et al., 2023b, 2023a) and the mechanical properties are presented in Table 1 (O’Brien et al., 2004; Tsiampousi et al., 2017). A non-linear anisotropic variation of permeability with mean effective stress was applied to all layers (Taborda et al., 2023).

$$k_v = k_{y,ref}\, e^{ap'} \# \tag{1}$$

where $k_{y,ref}$ is the reference permeability along the y direction, k_v is the current vertical permeability, p' is the mean effective stress and a is a fitting parameter set to 0.007 (Kovacevic et al., 2007). A horizontal to vertical permeability ratio of 10 was used (Wongsaroj et al., 2013).

The coefficient of earth pressure at rest (K_0) was 1.2, 1.5 and 1.0 for WLC, ILC and LGC, respectively. The excavation was modelled in three undrained phases. For analysis A, the net infiltration comprising of precipitation, evaporation from bare ground and snow, intercepted evaporation and transpiration was implemented as a surface BC using the infiltration BC which is a dual BC that can switch from prescribed pore water heads to an inflow/outflow infiltration rate.The maximum and minimum allowable head was set to -0.5 m and -100 m, respectively(Nyambayo& Potts, 2010). For scenario B, all hydrological parameters except transpiration was applied at the soil’s surface using an infiltration BC.Transpiration was implemented as an internal BC using the outflow BC. It was assumed that the root zone area was divided into five sections and five internal BCs were implemented. The side BCs was set to impermeable. The bottom BC, coinciding with chalk was set to seepage. After completing the analysis, a parallel analysis was conducted that calculated the Factor of Safety (FoS), using the strength reduction methods (Tsiampousi et al., 2013).

4. Analysis Results (Safety)

Suction time series at various depths (Fig. 2(a)) show similar behaviour at 0.5 m depth for both analyses, with instances with higher suctions for analysis B. This is because for analysis A, outflow is implemented at the surface, and in analysis B, evaporation occurs at the surface and most of the transpiration is concentrated near the surface, since the root fraction is highest there (Fig. 1(a)).

At greater depths, differences become more visible. For example, at 1 m and 2 m depth, within and beyond the root zone, respectively, analysis B shows slightly higher suctions (up to150 kPa in September 2031), due to the presence of internal BCs. Beyond the root zone (2.5 m depth), the effects of transpiration are still noticeable (Tsiampousi et al., 2017).

The FoS timeseries (Fig. 2 (b)), indicate that differences in suction, translate to only minor FoS variations. This slope is not at failure and the observed differences in FoS are insignificant, with a maximum difference of approximately 0.3. Specific dates with higher suctions in analysis B (August 2026, September 2031, July 2032 andAugust 2040) reflect the trend that suctions diverge with depth, starting with nearly similar suctions near the surface (Fig. 3).Analysis B provides a more realistic pwp profile, as it captures water extraction throughout the entire root zone rather than being limited to the surface. Additionally, at certain time instances where analysis A indicates little to no suction, analysis B shows significant suction throughout the crosssection.

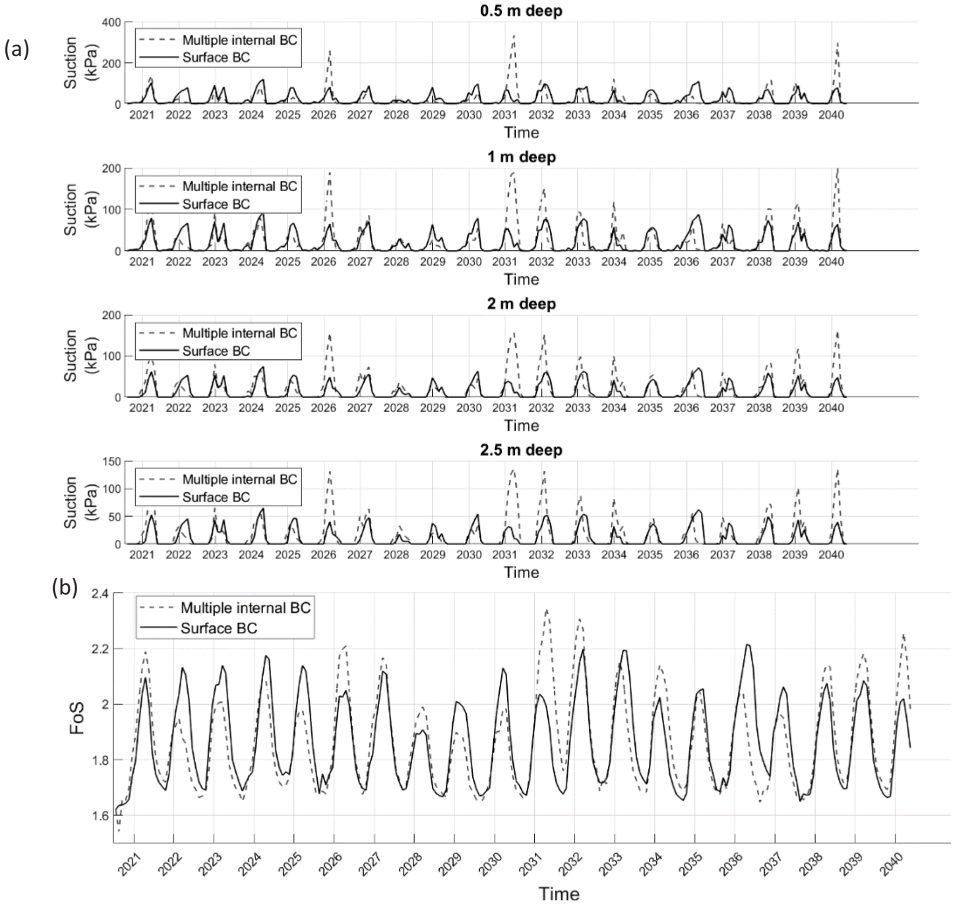

Fig. 2.(a)Suction vs time at 0.5 m, 1 m, 2 m and 2.5 m in depth for both analyses, (b) FoSvs time, for the years 2021 till 2040.

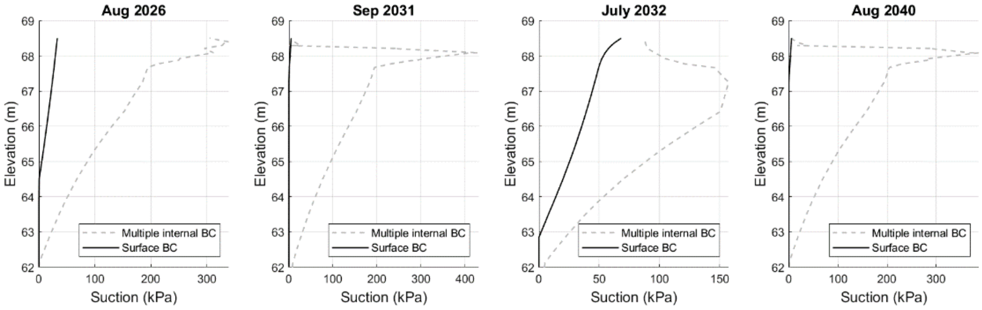

Fig.3. Cross sections of changes of suction vs depth at a few instances with max difference in suction for the two analyses.

Table 1. Mechanical properties for all three soil layers.

User Defined Soil Model parameters	Values	User Defined Soil Model parameters	Values	User Defined Soil Model parameters	Values
G_{ref} $[kN/m^2]$	955	b $[-]$	1.3	RK_{min} $[-]$	0.079
K_{ref} $[kN/m^2]$	1665	RG_{min} $[-]$	0.05	K_{min} $[kN/m^2]$	3000
p_{ref} $[kN/m^2]$	1	G_{min} $[kN/m^2]$	2000	φ [°]	23
m_G $[-]$	0.7	r_0 $[-]$	0.3E-3	c $[kN/m^2]$	7
m_K $[-]$	0.7	s $[-]$	1.1	ψ [°]	0
a_0 $[-]$	0.181E-3				

5. Conclusions

This paper investigates two approaches to modelling vegetation's hydraulic influence under future climate projections, i.e. transpiration: A) applying all hydraulic fluxes, including transpiration as a surface BC and B) applying all hydraulic fluxes, excluding transpiration at the surface,whileapplying transpirationat various depths within the root zone, using internal BCs. Negative PWPs (suction) and FoS were compared between the two analyses. Results showed minor differences in PWP distribution near the surface, as most of the transpiration occurs within the top 0.5 m of the soil. However deeper in the soil, differences in PWP became more apparent, as analysis B accounted for transpiration beyond the surface. Despite these variations, the FoS was not significantly impacted, indicating that a single surface BC is sufficient for capturing the necessary aspects for slope stability.

It is noteworthy that for the modelled tree type and the chosen root distribution function, transpiration is concentrated in the upper 0.5 m of the soil. It can be speculated that for plants with deeper root systems or if the maximum transpiration of a different plant type occurs in deeper depths of the soil, differences between these two methods could be more visible, potentially affecting PWP distribution and safety parameters.

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