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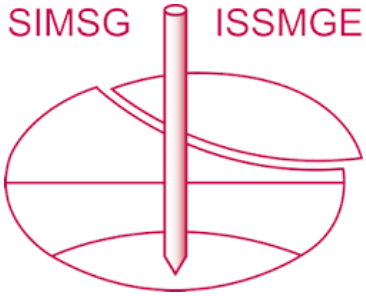

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A simplified modelling method of seasonal tree root-water uptake effects on pore-water pressure and ground subsidence

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ABSTRACT: Subsidence of buildings founded on clay has been increasingly reported in recent years due to seasonal soil shrinkage and swelling associated with root-water uptake by neighbouring tree(s). Modelling this kind of soil-vegetation-structure-climate interaction often involves complex root-water uptake models which require input of empirical plant parameters. This paper introduces a new and relatively simple modelling approach to simulate the effects of tree root-water uptake on seasonal pore water pressure changes and ground movement in unsaturated soils. In this approach, a root zone with a defined size is modelled by specifying multiple internal head boundaries in PLAXIS 2D, where hydromechanical behaviour of unsaturated soil can be simulated. The number, length and the magnitude of each head boundary can be flexibly adjusted according to a known root distribution and potential transpiration. Predicted changes of soil moisture induced by a mature deciduous Silver Birch and evergreen Leyland Cypress were validated against reported case histories. As a result of tree root-water uptake, significant differential settlement (as high as 1/100; depending on water uptake level, soil plasticity and seasons) could be induced near the edge of the root zone.

1 INTRODUCTION

Shrink/swell of fine-grained soil is seasonal and depends primarily on soil moisture/suction changes (Take and Bolton 2011; Leung and Ng 2016). The soil volume change could be magnified when vegetation is present (Driscoll 1983; Richards et al. 1983). Plant transpiration may improve soil strength (Kamchoom et al. 2014; Ng et al. 2016; Leung et al. 2016) but the associated soil volume change has significant implication to the engineering design of adjacent existing or new-built infrastructure, including shallow foundations and pipeline pavement (Bozozuk and Burn 1960; Driscoll 1983). The seasonality and different water demand of plant species (Bergh et al. 2003; Lutz et al 2010) would introduce differential ground settlement, hence causing structural integrity and serviceability problems. In current practice, safety clearance distance is defined between trees and adjacent shallow foundations based on tree height and, for a few of them, the water demand level and soil plasticity (e.g., NHBC 2011). Generally, these existing guidelines are empirical and based on limited field observation. Inputs from geotechnical engineers who apply soil mechanics and engineering principles are needed to improve the fundamental understanding of the soil-vegetation-structure-climate interaction.

Modelling plant effects on pore water pressure is challenging as it involves complex soil-plant-atmosphere interaction. Predicting plant-induced soil moisture loss and hence soil volume change requires the modelling of plant root-water uptake as well as hydromechanical modelling of unsaturated soil. There were attempts to incorporate a sink term in water flow model to capture plant root-water uptake (Indraratna et al. 2006; Nyambayo and Potts 2010). In this approach, transpiration is considered to be a function of soil matric suction (Feddes et al. 1976). The relations assumed are empirical and are developed based on the water uptake behavior of crop species, which is likely to be very different from mature woody tree species.

This paper proposes a new and simple modelling approach that overcomes the above limitation. Case histories that documented seasonal changes of soil degree of saturation induced by two mature trees with distinct water uptake behavior were used for model validation. The model was then used to predict seasonal changes of ground surface settlement profiles.

2 A NEW MODELLING APPROACH

2.1 *Review of plant-induced soil moisture changes*

Plant transpiration causes soil drying. Typically, the reduction of soil moisture, and hence pore water pressure, is the greatest at the centre of a plant, and the

magnitude reduces with distance both vertically and horizontally (Biddle 1983; Ng et al. 2013). Biddle (1983) and Pollen-Bankhead and Simon (2010) both highlighted that inter-species soil moisture variations were greater than intra-species one. Deciduous trees tend to have relatively higher water demand than evergreen trees (Arora et al. 1996; Hernandez-Santana et al. 2016), resulting in larger reduction of soil moisture during summer (MacNeil et al. 2001; Pollen-Bankhead and Simon 2010). On the contrary, during winter, deciduous trees would shed their leaves to reduce transpiration in order to maintain tree water level for survival (Kikuzawa 1983; Barboni et al. 2004). Tree-induced soil moisture changes during this period of year is generally minimal. On the other hand, evergreen species have fairly constant water demand and the difference in soil moisture reduction between summer and winter may be mainly due to atmospheric conditions (i.e., changes in Relative Humidity, temperature and solar radiation).

Case study reported by Biddle (1983) was used for model validation. Biddle (1983) monitored the patterns of soil moisture reduction during summer from isolated Silver Birch (SB; deciduous tree) and Leyland Cypress (LC; evergreen tree). The trees have an average height of about 10 m. All trees were grown within the areas of moderate shrinkage potential, such as London clay and Boulder clay.

2.2 *Modelling method*

Root zone is represented by multiple horizontal internal head boundaries (Figure 1). The number and length of each hydraulic boundary can be adjusted depending on the root distribution of a specific species. The head specified in each summer and winter can also be adjusted flexibly so that the rate of water being extracted from the root zone are equivalent to the potential transpiration (PT). PT is taken to be the difference between potential evapotranspiration (PET) estimated by Penman–Monteith equation (Monteith 1965) and potential evaporation (PE) by Penman equation (Penman 1948) and depends on the atmospheric conditions and plant characteristics.

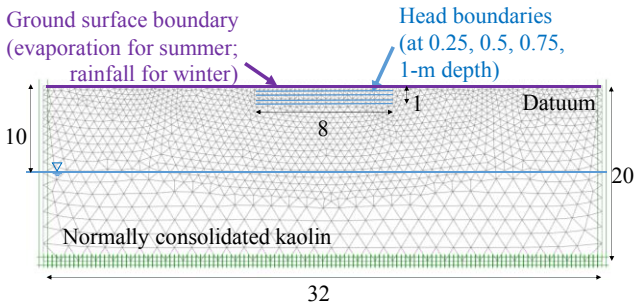

Figure 1. Finite element mesh and boundaries (all dimensions are in metres)

The major advantage of this simple approach is that each hydraulic boundary allows the simulation of soil moisture loss and the distribution of pore water pressure within the root zone of any specific plant species. Because of the great flexibility of setting the time-dependent internal hydraulic boundaries during an analysis, soil moisture changes by SB or LC during summer or winter can be simulated. The plant-induced soil moisture change can then be fed to any existing hydromechanical model of unsaturated soils for predicting the corresponding soil volume change during summer and winter. Indeed, this simplified approach considers plant root-water uptake for mainly a snapshot of a short period where the climate is relatively constant. Prediction of longer-term transient change of soil moisture/suction requires more complex modelling method using, for example, sink term (e.g., Feddes et al. 1976).

Table 1. Summary of typical atmospheric conditions and plants characteristics during summer and winter

Parameter	Value	
	Summer	Winter
Relative Humidity (RH; %)	70	95
Temperature (T; °c)	25	5
Radiant Energy (R_n; MJ/d/m^2)	15	8
Wind velocity (W; m/s)	1.5	1.5
Slope of vapour pressure curve (Δ)	0.19	0.06
Latent heat of vaporisation (λ; MJ/kg)	2.44	2.49
Saturated vapour pressure (e_s): kPa)	3.17	0.87
Actual vapour pressure (e_a: kPa)	2.22	0.83
Psychometric constant (γ: kPa/°c)	0.07	0.07
Aerodynamic resistance (r_a: s/m)	65.63	65.63
Surface resistance (r_s: SB; s/m)	57.14	181.82
Surface resistance (r_s: LC; s/m)	66.67	66.67
Leaf Area Index (LAI: SB)	3.50	1.00
Leaf Area Index (LAI: LC)	3.00	3.00

3 NUMERICAL ANALYSIS

Two coupled seepage-deformation analyses were performed using Plaxis 2D (Plaxis 2017), which is capable to model the nonlinear hydromechanical behaviour of unsaturated soil. Both analyses considered a green field of compacted kaoline clay, which the mechanical and hydraulic properties are known and thus suitable to evaluate the performance of the proposed modelling approach. The first and second analyses aim to simulate soil moisture change and hence ground surface settlement induced by root-water uptake of SB and LC, respectively (Table 2). One-year period, which consists of a 180-day summer and 180-day winter, was considered in both cases. Typical atmospheric conditions and plant characteristics for the case study (Biddle 1983) are summarised in Table 1.

3.1 *Finite element mesh and boundary conditions*

Figure 1 shows a typical finite element mesh adopted for analysis. All boundaries were specified to be per-

meable, except the ground surface, where either evaporation or rainfall flux boundaries were applied. An initial water table was considered at 10 m depth, generating an initial hydrostatic pore water pressure distribution. Both the side boundaries were horizontally constraint, whereas both vertical and horizontal constraints were applied at the bottom boundary. The root zone (8-m width and 1-m depth) was modelled via four head boundaries. The magnitude of head applied in each of these boundaries depend on the field observed soil moisture/suction distribution. The total water outflow per unit area from all these boundaries would be set equal to the difference between PET (Equation 1) and PE (Equation 2):

$$PET = \left[\frac{\Delta(R_n - G_s)}{\Delta+\gamma\left(1+\frac{r_s}{r_a}\right)} + \frac{\rho C_p(e_s - e_a)/r_a}{\Delta+\gamma\left(1+\frac{r_s}{r_a}\right)}\right] \quad (1)$$

where Δ is slope of vapour pressure curve (kPa°C^{-1}); R_n is radiant energy (MJm^{-2}d^{-1}); G_s is soil heat flux density (Jm^{-2}d^{-1}) (assumed negligible); ρ is air density (kgm^{-3}); C_p is specific heat of air (kJkg^{-1}°C^{-1}); e_s is saturated vapour pressure (kPa); e_a is actual vapour pressure (kPa); γ is psychometric constant (kPa°C^{-1}); r_s is surface resistance (depending on LAI of each species; sm^{-1}) and r_a is aerodynamic resistance (sm^{-1}).

$$PE = \left[\frac{\frac{\Delta R_n}{\lambda}+\gamma\left(0.165(e_s - e_a)\left(0.8+\frac{u}{100}\right)\right)}{\Delta+\gamma}\right] \quad (2)$$

where λ is latent heat of vaporisation (MJkg^{-1}) and u is wind speed (ms^{-1}).

When modelling root-water uptake by SB, the head boundaries were activated during summer but they were "switched off" during winter. For LC, the head boundaries were activated for all year round, but the magnitude of head applied would be different from that of SB case, depending on plant characteristics and atmospheric condition. For both species, during summer, a constant PE rate of 5 mm/d was specified along the entire ground surface, according to atmospheric parameters from Table 1. and Eq. (2). During winter, the PE boundary was removed and a rainfall flux of approximately 5 mm/d (i.e., equivalent to rainfall of 900 mm for 180 days) was applied. This is comparable to typical rainfall intensity in UK and most parts of Europe (Jenkins et al. 2009; MeteoSchweiz 2017).

Table 2. Summary of numerical runs

Boundary depth (m)	Total head (m)			
	SB		LC	
	Summer	Winter	Summer	Winter
0.25	-7	0	-5	-3
0.5	-15		-2	0
0.75	-3		-1	0
1	-2		-1	0

3.2 *Constitutive model and soil parameters*

Hypoplastic model for unsaturated soils (Masin and Khalili 2008) was used to simulate the hydromechanical behavior of unsaturated compacted kaoline in Plaxis. Bishop's effective stress principle modified by Khalili and Khabbaz (1998) was used to model suction-dependent shearing and volumetric behavior. All mechanical parameters required for the model were calibrated based on the triaxial tests reported by Sivakumar and Wheeler (2000) and Wheeler and Sivakumar (2000). The soil water retention curve of the compacted kaolin was from Tripathy et al. (2014) and it was best-fitted by van Genuchten (1980) equation. The fitted curve was then used to predict the hydraulic conductivity function (van Genuchten 1980). All input soil parameters are summarised in Table 3.

Table 3. Summary of soil parameters

Hypoplastic parameters	Value	Remark
Critical state friction angle (ϕ_c)	21	Sivakumar and Wheeler 2000
Initial void ratio (e_{ini})	1.150	
λ*	0.057	Calibrated against Sivakumar and Wheeler 2000
κ*	0.008	
N	0.982	
r	0.350	
n	0.100	
l	0	
m	10	
Over Consolidation Ratio	1	NC clay
Seepage flow parameters	Value	Remark
Residual degree of saturation (%)	5	Calibrated against Gallipoli et al. 2003
Saturated degree of saturation (%)	100	
g_n (or n)	1.6	
g_a (or α; 1/m)	0.04	
Pore connectivity (g_l)	0.5	
Saturated hydraulic conductivity (m/s)	1x10^{-9}	

4 RESULTS AND DISCUSSION

4.1 *Numerical modelling of soil moisture influenced by different plant species*

Figure 2 compares the measured (Figure 2(a)) and simulated (Figure 2(b)) contours of degree of saturation induced by SB after 180-day summer period. In the analysis, constant line-head boundaries of -7, -15, -3 and -2 m were applied at 0.25, 0.5, 0.75 and 1 m depth. Hence, the total amount of water extracted from these line-head boundaries (i.e., PT) was 5 mm/d, which is very close to the theoretical PT (4.87 mm/d) following a typical summer weather in the UK (Jenkins et al. 2009). Hence, it is not surprising to see close agreement between the measured and simulated degree of saturation. For Figure 2(b), the minimum degree of saturation of 82.7% was found at about 0.25-m depth, and it increased with distance away from the root zone. At 10 m away from the tree, the degree of saturation within 3-m depth was reduced to 97% due to evaporation.

Comparison of the measured and simulated degree of saturation of the LC is shown in Figures 2(c) and (d). In this case, the line-head boundaries at 0.25, 0.5, 0.75 and 1 m depth were assigned to be -5, -2, -1, -1 m during summer. As a result, the total water extracted from these boundaries was 4.4 mm/d, which matches well with the theoretical PT (4.29 mm/d). Good agreement between the measurements and simulation is thus found. The minimum degree of saturation induced by LC transpiration is 92.4%, which is higher than that by SB. This is expected because the LC has lower water demand than the SB.

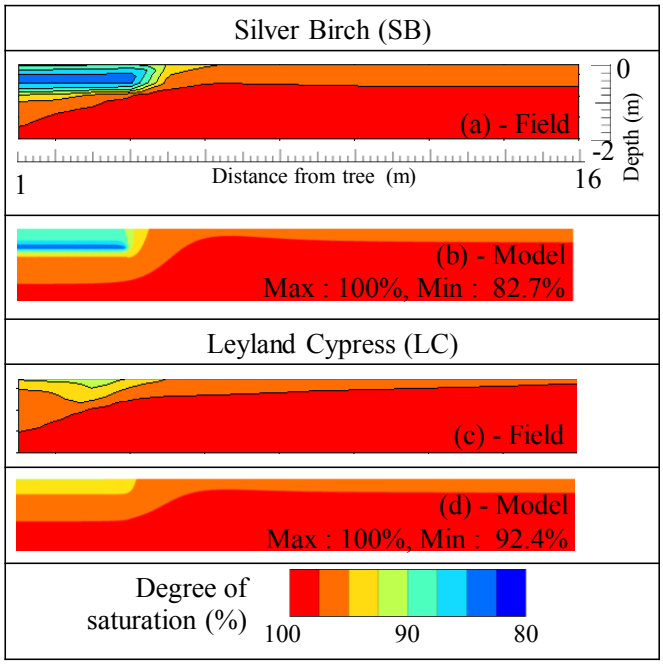

Figure 2. Measured and predicted soil degree of saturation induced by different plant species during summer

Unfortunately, no field data was reported for the same two species during winter, hence no comparison can be made. However, the same exercise performed for the summer case can be fully applied for the winter case. Due to leave shedding of SB, the theoretical PT became almost negligible (i.e., 0.04 mm/s) during winter. For LC, assuming that their traits do not have significant change over the year, the theoretical PT would be 1.03 mm/d (Table 1). By adjusting the four (or more) line-head boundaries in terms of head magnitude and the length of these boundaries, it is possible to determine an optimum condition where both the field degree of saturation and PT can be matched simultaneously

4.2 *Seasonal plant effects on soil hydrology*

Simulated pore-water pressure contours induced by SB during summer and winter are shown in Figures 3(a) and (b), respectively. After 180-day summer, significant suction (i.e., negative pore water pressure) was induced within the root zone, as expected, and the maximum value is about 160 kPa at 0.25-m depth. During winter when no transpiration occurred, suction at shallow depths were largely reduced upon rainfall infiltration. However, suction up to 20 kPa was preserved at 2-m beneath the root zone. This amount of suction preserved falls within the lower bounds (i.e., 10 – 50 kPa) observed in field and laboratory (MacNeil et al. 2001; Pollen-Bankhead and Simon 2010; Ng et al. 2016) This preserved suction was slightly higher (i.e., ~10 kPa) than that at 10 m away from root zone because the initial suction induced at the end of the summer was higher.

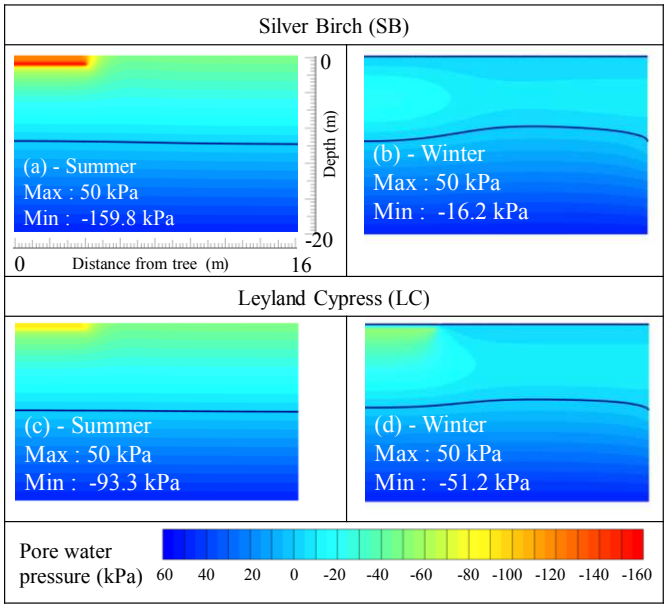

Figure 3. Effects of plant species on pore water variation during summer and winter

For the LC, the pore water pressure contour during summer was similar to that found in . However, the magnitude of suction induced within the root zone was much smaller (~100 kPa near the ground surface) because of the lower water demand. During winter, suction was again reduced due to rainfall infiltration, but because of transpiration by the LC, the final suction preserved within the root zone is 51 kPa, which is substantially higher than that in the SB case.

4.3 *Seasonal plant effects on ground surface settlement*

Figure 4 compares the predicted ground surface settlement between the SB and LC. After 180-day summer, the maximum ground surface settlement induced by the SB (up to 60 mm) almost doubled that by the LC's (up to 30 mm), both taken place within the root zone as expected. The greater displacement for the relatively high-water-demand SB case is because of the greater suction induced (Figures 3(a) and (c)) and hence soil shrinkage, compared to the LC. The influence zone of ground surface settlement is up to 2W, where W is the width of root zone.

After 180-day winter, ground heaves occurred in both cases. The SB does not transpire during winter

and thus the suction lost during rainfall (refer to Figure 3(b)) caused swelling. Since the suction lost occurred for the entire ground surface, there is an upward translation of the settlement profile by about 12 mm in Figure 4. For the LC, swelling within the root zone was less significant (i.e., less than 5 mm). This is because even during winter, the LC is still transpiring, although the amount was less than that in summer. The smaller suction lost in this case thus limits the amount of swelling. Outside the root zone, the soil swelling was similar between the SB and LC.

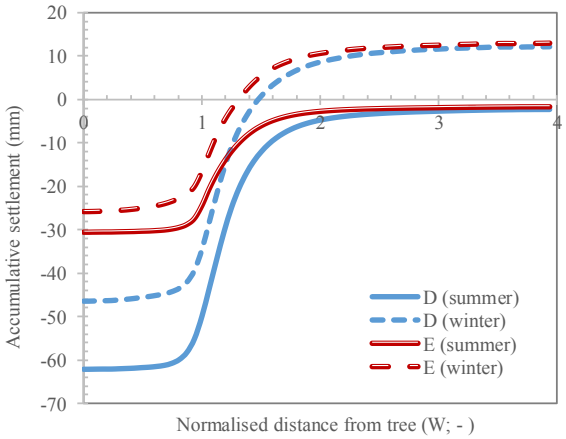

Figure 4. Effects of plant species on ground surface settlement during summer and winter

4.4 *Engineering implication*

Based on the simulation results shown in Figure 4, caution might be needed if a low-storey building is to be founded on a shallow (or slab) foundation near a tree, where suction gradient and hence settlement changes are the greatest. For the SB, if the foundation is 4 m wide and is located between 4 – 8 m distance from the tree centreline (i.e., at zero distance in Figure 4), the angular distortion of the building, upon soil shrinkage during summer, would be more than 1/100. According to Bjerrum (1963), this angular distortion is beyond the safety limit of structural damage. Considerable cracks would be expected in panel walls and brick walls. During winter, it is deemed inappropriate to estimate angular distortion since the foundation would shed the ground surface from rainfall, and one would expect a different settlement profile when the structure exists. With the identical building, the angular distortion of the building located near the LC was within the safety margin (i.e., < 1/100).

NHBC (2011) is one of the commonly used empirical guidelines for preliminarily assessing whether a shallow (or slab) foundation of a low-storey building should be constructed near trees, and if so, how far or minimum clearance distance should it be so as to minimise structural damage against serviceability limit state. The standard suggests that for medium plastic fine-grained soil (like the kaoline clay in this study), the safety distance of a building should be 1.25L and 0.75L (where L is the tree height) away from the SB and LC, respectively. From Figure 4, for either SB or LC, it seems safer to position the building at least 6 m away from the tree. This distance is less than that suggested by NHBC. Although soil swelling takes place during rainfall in all cases, the ground surface settlement beyond 6 m distance is rather uniform and would expect to induce only limited differential settlement. More accurate distribution of head boundaries would provide better simulation of soil movement due to specific tree species and mitigate any potential damage to nearby structures.

5 CONCLUSIONS

A new modelling approach for capturing the effects of seasonal root-water uptake by mature trees was proposed in this study. Root zone is modelled by multiple internal head boundaries, of which the number, length and head magnitude can be flexibly adjusted according to a known root distribution and potential transpiration. This modelling approach can be integrated into commercial finite element software where module of root-water uptake modelling is not available. This paper demonstrates examples of integrating the modelling method in PLAXIS 2D with an inbuilt hydromechanical constitutive soil model, Hypoplastic model for unsaturated soil. Hence, coupled effects of tree seasonal root-water uptake on soil volume change and hence ground surface settlement could be considered.

The modelling method has been validated by field case histories. Realistic profiles of the change of soil moisture due to root-water uptake were simulated for a deciduous Silver Bitch (SB) and an evergreen Leyland Cypress (LC). Although SB induced greater suction (i.e., up to 160 kPa at 0.25 m-depth) compared to LC (i.e., 93.3 kPa at 0.15 m-depth) during summer, water uptake by the SB was minimal during winter. The magnitude of suction retained was about 16 kPa, which was lower than that (51 kPa) by the LC.

The different seasonal pattern of root-water uptake between the SB and LC caused different ground surface settlement profiles. Since the SB has a higher water demand than the LC during summer, the peak ground settlement induced by the SB was three times higher. Hence, a much higher differential settlement (with an angular distortion of > 1/100) was found near the edge of the root zone of SB. This has negative implication to the structural integrity and serviceability for adjacent shallow slab foundations. For the water demand level of tree and soil plasticity considered in this study, the safety distance between tree and adjacent as per existing guidelines such as NHBC is found to be much further (i.e., more conservative) than what is predicted by the numerical simulation.

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