Modeling tree-induced ground subsidence in compacted clay: An investigation into the effects of contrasting tree species

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Abstract

The subsidence of structures founded on clay soils has been an increasingly prevalent issue in recent years, primarily due to the cyclic contraction and expansion of soil in response to root-water uptake by neighbouring trees and the seasonal variations. Traditional models for simulating the complex interplay between soil, vegetation, structure, and climate often entail intricate root-water uptake models that require extensive empirical data. This study employed a simplified modelling approach to assess the impact of tree root-water uptake on seasonal changes in pore water pressure and ground movement in unsaturated soils. By defining a root zone and incorporating multiple internal head boundaries in PLAXIS 2D, the hydromechanical behaviour of the unsaturated soil can be effectively modelled. The results of this model, which consider the soil moisture changes induced by mature deciduous Silver Birch and evergreen Leyland Cypress trees, were validated against reported case studies. Our findings suggest that significant differential settlements (ranging from 1/100 to 1/10, depending on water uptake, soil plasticity, and season) may occur near the edge of the root zone as a result of tree root-water uptake.

Keywords: Hypoplastic model, PWP, Ground subsidence, Root water uptake, Tree

1. Introduction

The subsidence of structures founded on clay soils has become a pressing concern in recent years, especially in Thailand where is most of infrastructures (i.e., roads and rail embankments) located on soft clay soil. This problem is mainly attributed to the cyclic shrinkage and swelling of the clay soils, caused by the uptake of water by trees and seasonal weather variations [1,2]. These repeated volume changes can lead to different subsidence problems, usually causing detrimental effects on the roads, foundations, and related infrastructure. The existence of nearby trees aggravates those infrastructure damages [3]. Roots play an important role in changing the soil moisture of soil through transpiration which greatly influenced by the tree water demand and seasonal variations [4–8].

It is well recognised that vegetation has various mechanical and hydrological impacts on ground stability. Vegetation can improve the shear strength of the soil by increasing the matric suction and also curtails soil movements [9–11]. In addition, vegetation also provides additional soil strength via root cohesion which can increase slope stability through root reinforcement of soil [12–14] and through the transpiration process depleting soil moisture, increasing the soil suction and shear strength further [5,10].

On the other hand, vegetation also has adverse effects, especially to infrastructure destruction [15]. This problem usually occurs in areas where the root growth of trees is approximately 2-3 meters [16]. In addition, the contraction and expansion of the soil due to the water uptake of plant roots which can cause a change in soil water content resulting in soil settlement [1]. Furthermore, seasonal effect and different water demands of plant species can cause different soil subsidence, creating structural integrity and maintenance issues [17,18].

Evergreen and deciduous trees of the tropical dry forests in southeast Asia [19] which have different water demand. Dry evergreen forest and dry deciduous forest are the main forest types extensively dispersed in north-eastern Thailand, each of which has a varied capacity to cycle nutrients [20,21]. In Indonesia, Over 70% of the island was covered by forest, which included moist deciduous forest, dry deciduous forest, and seasonal evergreen forest (MDF) [22]. [23] compared variations in the leaf characteristics, leaf gas exchange, and photochemical properties of drought-deciduous trees and evergreen trees in tropical dry woods, when the soil nutrients were different, but the rainfall was similar. In addition, [21] examined the root decomposition and associated mass loss and nitrogen release in two root types. Moreover, [24] monitored the patterns of soil moisture reduction during summer from isolated Silver Birch (SB; deciduous tree) and Leyland Cypress (LC; evergreen tree) during summer.

According to preceding overviews, the issue of subsidence in structures built on clay soils is a concerning issue, especially in regions where the soil is affected by the absorption of water by trees and seasonal weather variations. Thus, this study aims to investigate the comparison of two contrasting trees (evergreen and deciduous tree) on pore water pressure (PWP) and soil movement on the different seasons (wet and dry). This comparison expected would provide important information for policymakers, engineers, and environmentalists about tree planting in areas with soft clay soil, and to help mitigate the impact of soil subsidence on infrastructure. This paper used simplified numerical model to simulate tree root water uptake. The hypoplastic soil model was used in study which can accurately depict the non-linear behaviour and plastic strain building that occurs in unsaturated soil.

2. Methodology

2.1 Root modelling

Roots play an important role in changing the soil moisture of soil through transpiration which greatly influenced by the tree water demand and seasonal variations [5,6,8,10,25]. The moisture content of the soil drops around the roots as a result of transpiration which can lead to an uneven distribution of suction of surronding soil [26]. Generally, the loss of soil moisture consequently decreasing pore water pressure is greatest at the center of a plant and decreases vertically and horizontally with the distance [24,27].

In this study, deciduous and evergreen tree species was analysed for understanding the effect of those fluorescent species on PWP change and subsidence. Generally, deciduous trees have a substantially higher water demand than evergreens in the summer which lead in a greater decrease soil moisture [28–30]. However, to ensure tree survival during winter, the trees would reduce the transpiration with shedding their leaves [31]. In contrast, evergreen species have a relatively constant water demand, and the variation in soil moisture loss between summer and winter may be primarily attributable to atmospheric parameters (i.e., changes in Relative Humidity, temperature and solar radiation)[23].

In this research, A field study published by Biddle [24] was utilized to validate the simulation model. The height of the tree (h) was simulated at 10 m based on the field conditions conducted by Biddle [24], which is the average height of a tree in 10 years [32]. Biddle [24] observed the patterns of summertime soil moisture loss from Silver Birch (deciduous tree) and Leyland Cypress (evergreen tree).

2.2 Mesh and boundary conditions

In simulation, Plaxis 2D [33] was used to conduct two coupled seepage-deformation analyses for unsaturated soil condition. Both analyses employed a compacted kaoline clay for the mechanical and hydraulic properties. As depicted in Figure 1, a finite element mesh with a 32 m-wide level ground was used for investigation. The thickness of the model was 20 cm with the initial water table was 10 m depth. Both side limits were horizontally constrained, whereas both vertical and horizontal constraints were applied at the bottom boundary.

The root zone is simplified by multiple horizontal internal head boundaries approached by [34]. The number and length of each hydraulic boundary can be modified depending on the root distribution of a specific tree. In addition, the specified head (i.e., root water uptake) for dry and rainy seasons can be adjusted based on the total amount of water extracted from the root zone which is equivalent to the potential transpiration (PT). In this analysis, the root was modelled by 4 lines of head boundaries with a thickness of 0.25 m for each line because Biddle [24] found that *both trees* show a localized effect on PWP and volumetric water change within the top 1 m-depth. In addition, these impacts did not extend beyond a distance of 0.4h from the tree's centre, so representing a root model with an overall width of 8 meters. The magnitude of head applied in each of these

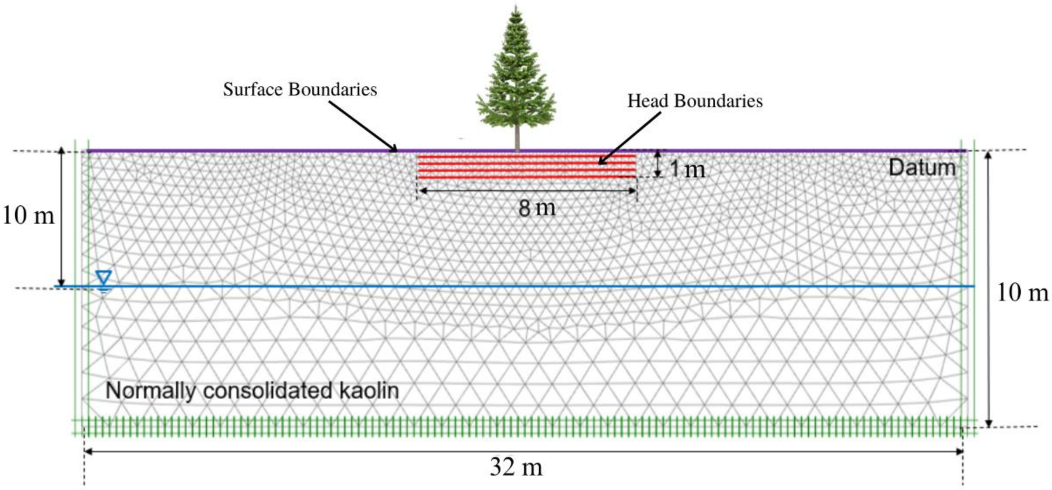


Figure 1 Model geometry

boundaries based on the field observed soil moisture/suction distribution. The total water outflow per unit area from each of these boundaries would be equal to the difference between PET (Equation 1) and PE. (Equation 2):

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

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}).

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

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

In addition, during the dry and wet seasons, the evaporation and rainfall flux bounds were applied to the model's ground surface, respectively. According to Thailand's Meteorological Department [35], during wet season in 2020, the precipitation was about 900 mm for 180 days, or 5 mm/day. Hence, the soil evaporation indicated by total water outflow was fixed at 5 mm/day throughout the entire ground surface during 180 days of dry conditions. During the wet season, however, the outflow flux boundary was deleted and an input flux boundary of roughly 5 mm/day was implemented.

Table 1 Summary of Numerical Runs

Boundary depth (m)	Total head (m)			
	Silver Birch		Leyland Cypress	
	Summer	Winter	Summer	Winter
0.25	-7	0	-5	-3
0.5	-15		-2	0
0.75	-3		-1	0
1	-2		-1	0

2.3 Soil Model

Due to the seasonal cycles influence on the shrinking and swelling of soil behaviour, which leads to soil settlement, it is essential to be able to accurately forecast the deformation behaviour of unsaturated soil. [36] hypoplastic model for unsaturated soil was applied in this investigation. The hypoplastic clay model can depict soil behaviour based on plasticity concept, which permits the accumulation of plastic strains in soil. It has been demonstrated that this model was successfully predicts the nonlinear behaviour of clay soils under monotonic loading at small to large strain values [36,37]. The mechanical characteristics were calibrated based on the triaxial tests given by [38]. The soil water retention curve of compacted kaolin by Tripathy et al. [39] was calibrated based on van Genuchten's [40] equation, then employed to predict the hydraulic conductivity function. Table 2 provides a summary of all soil input characteristics.

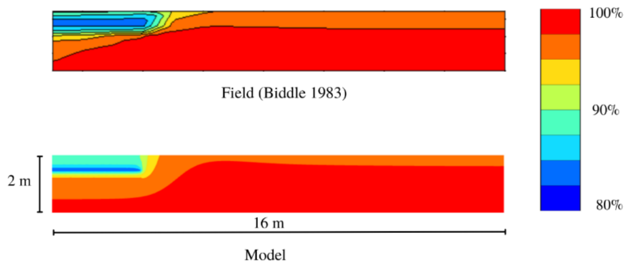
Table 2 Soil Parameters

Hypoplastic parameters	Value	Remark
Critical state friction angle (φ_c)	21	Sivakumar & Wheeler 2000
Initial void ratio (e_{ini})	1.150	
λ^*	0.057	Calibrated against Sivakumar & 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)	1×10^{-9}	

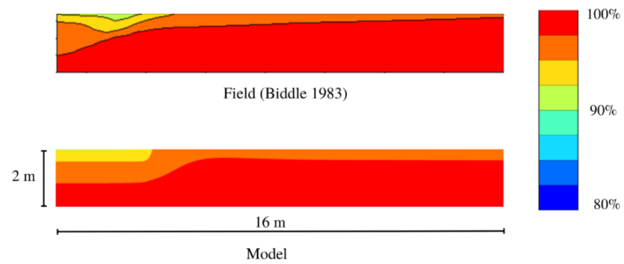
3. Results and discussion

Figure 2(a) and 2(b) shows the measured and simulated contours of saturation degree generated by Deciduous and Evergreen tree, respectively after 180 days of summer. Both of tree species resulted close agreement to measures degree of saturation in the field. This expected due to the total amount of water extracted from these line-head boundaries (i.e., PT) was 5 mm/d, which is closely same with the theoretical PT (4.87 mm/d) for deciduous tree. However, for Evergreen tree because 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 thus resulting the total water extracted from these boundaries was 4.4 mm/d which almost similar with the theoretical PT (4.29 mm/d).

A minimum saturation level of 82.7% at a depth of 0.25 meters, which increased with distance from the root zone. The degree of saturation within 3-meter depth decreased to 97% at 10 meters from the tree because of evapotranspiration. In other hand, Evergreen tree transpiration induces a minimum degree of saturation of 92.4%, which is higher than Deciduous tree. This is expected due to the evergreen tree has lower water demand than Deciduous tree.



(a) Deciduous tree (Silver birch)



(b) Evergreen tree (Leyland cypress)

Figure 2 Degree of saturation during summer

3.1 *Seasonal plant effects on soil hydrology*

The contours of simulated pore-water pressure for each species during the summer was shown by Figure 3. A ssignificant negative pore water pressure (suction) was created inside the root zone following a 180-day summer with a maximum value of around 160 kPa and 93 kPa at 0.25 m depth for Deciduous (Silver birch) and evergreen tree (Leyland cypress), respectively.

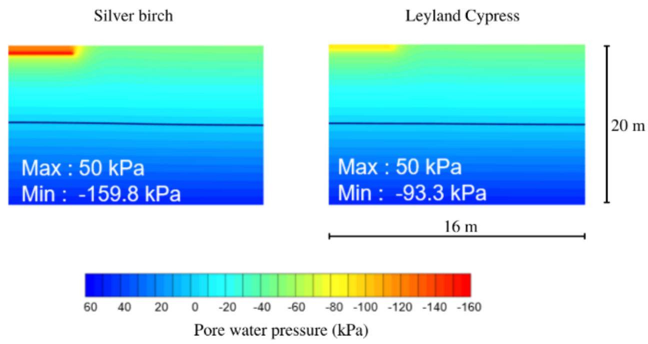


Figure 3 Effects of plant species on pore water variation during summer

In addition, it was found that the soil at shallower depths experienced higher suction values and tended to gradually decrease with increasing depth for both tree species. This happen because the shallowest soil layers more influenced with seasonal and atmospheric conditions (such as rain, humidity, solar radiation, and air temperature) resulting greater evapotranspiration compared to the deeper soil layers [6,25,41].

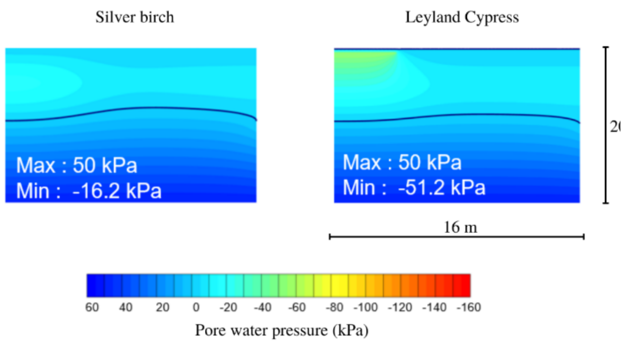


Figure 2 Figure 3 Effects of plant species on pore water variation during winter

Figure 4 shows the pore water pressure during the winter for both tree species. During the winter, when there was little transpiration, rainwater infiltration significantly lowered suction at shallow levels. Nonetheless, up to 20 kPa of suction was maintained 2 meters below the root zone. This level of suction preservation falls within the 10 to 50 kPa range found in the field and laboratory [30,42]. Suction during winter dropped drastically (to 16.2 kPa) for the Silver birch tree. However, the suction preserved inside the Leyland cypress root zone is 51 kPa, which is significantly greater than that of the Silver birch. In addition, the contour of the Evergreen pore water pressure during winter was identical to during the summer (93.3 kPa). Due to the decreasing water demand, the amplitude of suction within the root zone was significantly reduced (100 kPa at the ground surface).

3.2 Seasonal plant effects on ground surface settlement

Figure 5 compares the settlement experienced by both of tree species. After a 180-day summer, the Deciduous tree (Silver birch) experienced the highest settlement up to 60 mm at the root zone which was almost twice higher that of the Evergreen tree (Leyland cypress) (up to 30 mm). This higher displacement for the comparatively high-water-demand Deciduous tree scenario is due to the higher suction caused (Figure 3). In addition, the influence zone of surface ground settlement experienced up to two times of root zone width (2W).

Ground heaves occurred after for both tree species a winter of 180 days. Deciduous tree lost the suction because of does not transpire during the winter (Table 1) which leads the soil to swelling. Figure 5 depicts a 12 mm upward of the settlement profile because suction loss occurred over the whole ground surface. For the Lyland cypress, enlargement of root zone was less significant (i.e., less than 5 mm) because of the continued transpiration even throughout the winter, however still less than transpiration during the summer. On the other hand, both of tree species experience the same settlement apart from the root zone.

Based on the simulation results depicted in Figure 5, extra caution may be required if a low-rise structure constructed on a shallow (or slab) foundation near a tree, where suction gradient and consequently resulting the higher settlement effects. For the Silver birch, if the slab foundation is 4 m wide located between 4 to 8 m from the tree's centreline, the angular distortion of the building due to soil shrinkage during the summer would exceed 1/100. This angular distortion exceeds the structural damage safety limit [43]. The stability of the

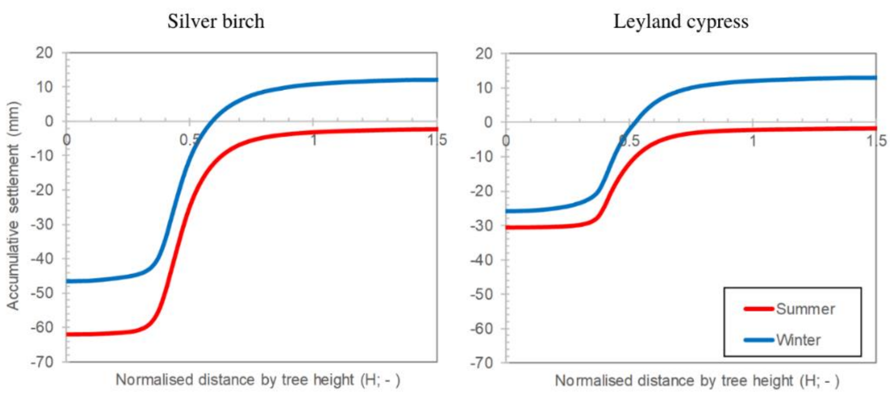


Figure 3 Plant effect on ground surface settlement during summer and winter

building must be evaluated in this case. During the winter, it is improper to predict angular distortion since the foundation would shed the ground surface from precipitation and a different settlement profile would be anticipated when the structure is there. The angular distortion of the same building positioned near the Leyland cypress fell within the safety margin (i.e., <1/100).

4. Conclusions

The subsidence of structures built on clay soils has become a growing concern due to the cyclic expansion and contraction of soil caused by tree root-water uptake and seasonal variations. This study utilized a simplified modelling approach to evaluate the impact of tree root-water uptake on seasonal changes in pore water pressure and ground movement in unsaturated soils. By defining a root zone and integrating multiple internal head boundaries in PLAXIS 2D, the hydromechanical behaviour of unsaturated soil can be effectively modelled. The Silver birch and Leyland cypress was chosen for the modelling which represented the Deciduous and Evergreen tree, respectively. The result shows that Both of tree species resulted close agreement to measures degree of saturation in the field. In terms of PWP, comparing with Silver birch, Leyland cypress resulted almost similar maximum PWP during the summer and winter period. In addition, the Silver birch had a greater water demand than the Leyland cypress during the summer which about three times more peak ground settlement. Therefore, near the Silver birch root zone experienced a greater differential settlement (with an angular distortion of > 1/100).

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