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Micromechanical study of potential scale effects in small-scale modelling of sinker tree roots

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Abstract

When testing an 1:*N* geotechnical structure in the centrifuge, it is desirable to choose a large scale factor (*N*) that can fit the small-scale model in a model container and avoid unwanted boundary effects, however, this in turn may cause scale effects when the structure is over-scaled. This is more significant when it comes to small-scale modelling of sinker root-soil interaction, where root-particle size ratio is much lower. In this study the Distinct Element Method (DEM) is used to investigate this problem. The sinker root of a model root system under axial loading was analysed, with both upward and downward behaviour compared with the Finite Element Method (FEM), where the soil is modelled as a continuum in which case particle-size effects are not taken into consideration. Based on the scaling law, with the same prototype scale and particle size distribution, different scale factors/***g***-levels were applied to quantify effects of the ratio of root diameter (d_r) to mean particle size (D_{50}) on the root root-soil interaction.

1. Introduction

Understanding tree root anchorage behaviour under lateral loads has long been of interest in forestry, where heavy winds, predicted to be stronger due to the increase of power of major Atlantic tropical hurricanes, are the main causes of destruction in European forests (McCarthy et al., 2010) and responsible for more than 50% of damage in European forests (Schelhaas et al., 2003). In addition, it is of interest in Civil Engineering, where windthrown trees in sloping ground may be a trigger for landslides (Jakob and Lambert, 2009) and a potential threat to life (e.g. Storm Ali, United Kingdom, September 2018). Fallen trees may also disrupt transportation services, such as occurred in the UK during Storm Doris in February 2017, where overhead power lines on the West Coast Mainline were brought down.

In recent decades, an increasing body of research has used 1:*N* scaled root models (e.g. Harnas et al., 2016; Liang et al., 2015; Zhang et al., 2018), which can be tested in the lab, either under 1***g*** or elevated-gravity to study root-soil interaction. In order to avoid unwanted boundary effects from the model container, a high value of *N* is desired; however, this may cause scale effects if the root is over-scaled, which leads to overestimation of root-soil interaction.

The Distinct Element Method (DEM) is capable of changing the particle-scale properties and is therefore suitable for the investigation of scale effects (e.g. Athani et al., 2017; Cerfontaine et al., 2021). However, in general, there exists a limitation on the total number of particles for obtaining DEM simulation results within a reasonable computational time. An approach to minimise the computational effort is to reduce the total number of particles by increasing the particle size (Ciantia et al., 2016). However, this in turn changes the structure-particle size ratio, possibly resulting in scale effects.

As shown in Figure 1(a), under external lateral loading (e.g. a windstorm), individual roots (excluding the taproot) are idealised to be either lifted-up or pushed into the soil. The aim of this study is to numerically model the sinker roots, and then to investigate the influence, if any, of potential scale effects that may arise in physical model tests of sinker roots moving upward and downward. To this end, 3D DEM numerical simulations were employed to replicate the behaviour of sinker roots of different diameters interacting with a granular bed. Similar to real small-scale physical modelling with the centrifuge employed, the prototype dimension of the root and particle size distribution of the soil were kept constant, while different scale factors/gravitational accelerations (***g***-levels) were applied. The results were then compared with equivalent FEM simulations, where the soil is considered as a continuum and hence not incorporating particle-size effects.

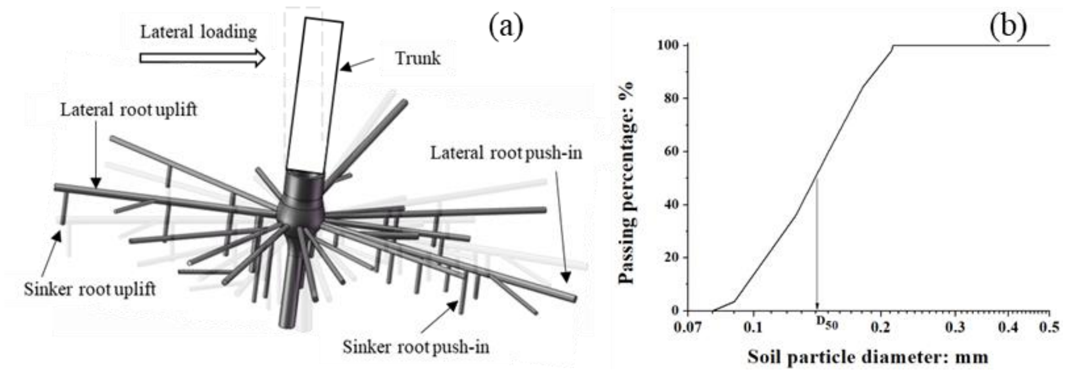

Figure 1 (a): Simplified root system under external lateral loading; (b): Particle size distribution of HST95 sand

2. Numerical setup

The sinker root was modelled as a rigid cylinder with interface friction coefficient 0.465 and first simulated in Particle Flow Code (PFC) 3D 5.0.35 (Itasca Consulting Group, 2016), where the virtual soil bed, with the density of 1.65 g/cm^3, was created using the periodic cell replication method (PCRM, Ciantia et al., 2018). The model soil was to replicate Congleton HST95 sand behaviour, with its particle size distribution shown in Figure 1(b) and the detail of soil calibration is described in Sharif et al., (2019). Following previous research (Sharif et al., 2021), the particle size was scaled up in the radial direction with increasing radial distance from the root to minimise the computational time. However, particles in the central zone where the root existed were 1:1 scaled. The test chamber was designed to be wider than $18d_r$, (where d_r is root diameter) with the soil thickness beneath the root larger than $2d_r$ and $8d_r$ for upward and downward movement cases, respectively. Further increasing the width of the chamber, or the distance to the bottom was systematically checked to guarantee no significant effects on the root behaviour. Following Ciantia et al. (2019), the root was displaced vertically, at a constant speed of 4 mm/s to set inertial numbers in each case lower than 10^{-3}.

The prototype root investigated in this study was 60 mm in diameter and 240 mm in length, buried at 130 mm depth (distance between top of the root and soil free surface, dimensions all at prototype scale) according to a *Pinus pinaster* tree root system (Zhang et al., 2020). The principal of numerical simulations was to scale down the length, diameter and burial depth of roots by N times and scale up the gravitational acceleration to maintain the same prototype virtual model and stress level but without scaling particle size. By doing so, the number of soil particles surrounding the roots was intentionally decreased. The advantage of this method is that the ratio of root burial depth to diameter was unchanged. The force at prototype scale could be obtained by multiplying measured force of the scaled root by N^2. In theory, the response at prototype scale should be the same if no scale effects are present.

Corresponding FEM simulations were also conducted by the two-dimensional (2D) finite element software PLAXIS using the same dimensions as DEM for comparison.

3. Results

As shown in Figure 2(a), the prototype uplift capacities of sinker roots with different $\boldsymbol{g}$-levels applied were all approximately 0.15 kN in FEM. In DEM, there existed a negative linear relationship between the pull-out force and d_r/D_{50} ratio, indicating the significance of the scale effects. The uplift force of a 0.8 mm model sinker root (corresponding d_r/D_{50} = 6) was approximately 2 times higher than that of a 3 mm model root (corresponding d_r/D_{50} = 21), also indicating that the increase of scale factor/$\boldsymbol{g}$-level from 20 to 75 in the physical modelling would 100% overestimate the vertical root pull-out capacity. However, when d_r/D_{50} reached 21 (corresponding N = 25), the results were quite similar between DEM and FEM.

In terms of sinker roots moving downwards, the prototype force at 10 mm prototype displacement (16.67%d_r) was extracted from curves of roots with different diameters for comparison (Figure 2(b)). It can be seen that the decrease of root diameter from 3 mm (d_r/D_{50} = 21) to 0.8 mm (d_r/D_{50} = 6) resulted in 40% higher push-in resistance, suggesting non-negligible scale effects. Given that the force investigated here was composed of shaft and base resistance, and the shaft skin frictional resistance was largely affected by scale effects (Figure 2(a)), the base bearing capacity was extracted separately for further investigation. As shown in Figure 2(b), in general, no significant change was observed on the base resistance in DEM simulations, indicating that the base resistance was not affected by the reduced scale of the root model, which was consistent with the corresponding FEM simulations.

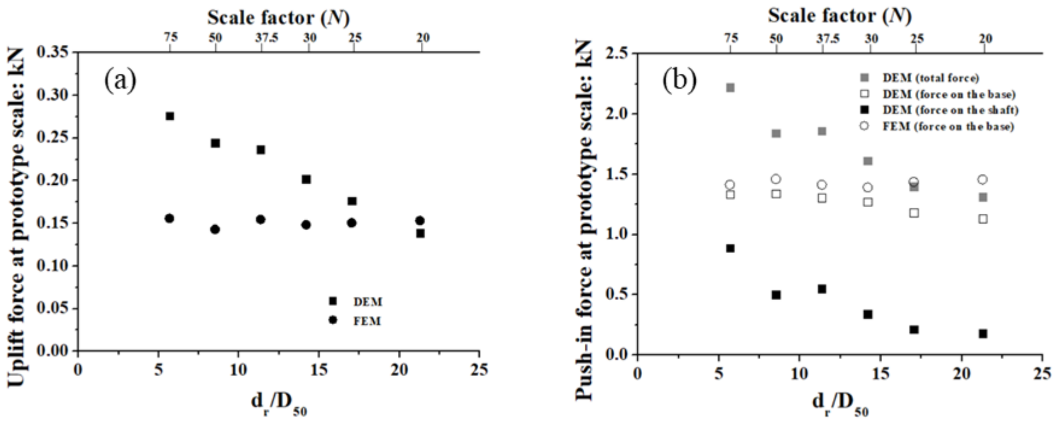

Figure 2: Force at prototype scale of sinker roots with the same prototype dimension but different scale factors N. (a) Upward movement; (b) Downward movement.

4. Conclusions

This study has presented an investigation into potential scale effects that may arise in physical model tests of sinker root-soil interaction. 3D DEM numerical simulations were employed to work as a virtual centrifuge to replicate the behaviour of sinker roots of different diameters interacting with a granular bed. It was found that a change in scale factor did not significantly affect the end-bearing capacity, however, in terms of the shaft resistance of the sinker root, the scale effect was significant. This reveals potential scale effects when conducting small-scale tests on sinker root-soil interaction and also identifies a risk of unsafe design when upscaling small-scale laboratory measurements to meter-size piles used in practice.

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