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NUMERICAL GEOTECHNICAL MODELING OF TREE ROOT-SOILINTERACTION: AN INSIGHT INTO THE EFFECTS OF UNCERTAINTIES IN ROOT GEOMETRY ON OVERTURNING FAILURE

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Tree roots are important in enhancing soil strength, mitigating erosion, and improving slope stability.This paperstudies the morphological impacts of total root system sizethrough a new numerical approach for analysing root-soil interactions in a stochastic modeling framework. Root systems were simulated using the Space Colonization Algorithm (SCA), which generates realistic three-dimensional geometries accounting for uncertainties in root configurations. These geometries were integrated into a Finite Element Method (FEM) model in Plaxis 3D, where root branches were modeled as embedded beams with elastoplastic behavior. Simulations evaluated the influence of root geometry, lateral extension, and depth on the mechanical response of the root-soil system under static lateral loads (Simulating the effect of wind load). Results indicated that deeper roots significantly enhance overturning resistance by anchoring the tree vertically, while greater lateral root extension further stabilizes the system, contributing to a higher maximum overturning moment.

Keywords: Tree roots, Root-soil interaction, Tree anchorage, Space colonization algorithm, Embedded beam.

1. Introduction

Tree roots form a dense network that contributes to mitigating superficial erosional phenomena and improves soil stability by increasing the soil mechanical strength and resistance to shear forces. Integrating vegetation into slope management practices provides a nature-based approach to mitigate slope failure hazards while fostering sustainable land management. Understanding the root-soil interaction behavior under lateral loads imposed on the tree through natural hazards such as windstorms has been of interest in designing effective erosion mitigation and slope stabilization strategies. Root-soil interaction studies are also important for assessing the stability of trees, especially in areas prone to extreme weather conditions, where uprooting can pose serious ecological and safety challenges.Failure of root-soil systems can occur due to root failure, which may involve roots being pulled out, bending, orshear failure of roots. Additionally, failure can result from soil shear failure. Characterizing the specific failuremode is challenging due to the intricate interaction between roots and soil.Various parameters, includingsoil properties, axial, shear, and bending resistance of roots, influence this interaction. Root architecture is another factor that plays an essential role in tree pull-out resistance. General categories for root architectures have been previously suggested(Crow, 2005; Fitter, 1987; Fitter & Stickland, 1991; Yen, 1987) although each tree's root configuration can vary significantlywithin species due to genetic and environmental factors.Two types of simplified herringbone-like root FEM models with differences in the insertionangle of lateral roots were developed by Fourcaud et al. (2008). Distinct behaviors in terms of anchorage strength and modes of failure were observed, which were influenced by the soil type and the morphology of the root systems.Dupuy et al. (2007) developed a more advanced 3D FEM model using beam elements to incorporate realistic root system architectures derived from destructive field tests. This model aimed to analyze how roots anchor a tree during uprooting and assess the contribution of various root components to overall tree stability.Research by Pang et al. (2024)revealed a positive correlation between the maximum uprooting force and the total root length. The findings also indicated that the number of inclined first-order roots significantly influenced the maximum uprooting force.

Developing methods to replicate and study various root system shapes can significantly help in understanding tree stability and their resistance to mechanical failures like uprooting (Dupuy et al., 2007). The modeling of root-soil interaction phenomena is fraught with significant uncertainties stemming from the difficulty in measuring, estimating, and representing the geometric, geomechanical, and hydrogeological features of root-soil systems. This paper illustrates selected salient aspects and results of an ongoing research effort aimed at developing a novel geotechnical numerical modeling approach for the investigation of root-soil interaction addressed here. The indetermination in the spatial structure of root-soil systems is addressed by adopting the hypothesis of randomness of root geometry and modeling root branches through a stochastic process using a space colonization algorithm combined with embedded beam elements in Plaxis 3D software (*PLAXIS 3D*, 2024). The paper examines the impact of different root geometries and configurations on overturning moment within the root-soil system and discusses the dependency and variability in failure mechanisms from root structure and arrangement.

2. Methodology

Previous research utilized recursive or fractal patterns to create realistic representations of tree geometry(Hidayat et al., 2020; Prusinkiewicz et al., 2001). These modeling approaches were progressively refined to incorporate variability and adapt to environmental influences. While most studies apply recursive methods to above-ground tree structures, studies including van Noordwijk et al. (1994)suggested that root architecture could also be modeled using fractal geometry, emphasizing the importance of proximal roots in predicting overall root distribution. However, Sachs and Novoplansky (1995)highlighted the limitations of purely recursive models, noting that environmental factors significantly shape tree development.

In this study, an alternative approach based on an ongoing research on root-soil interaction, the Space Colonization Algorithm (SCA), is applied to simulate root systems by generating a three-dimensional boundary to define the overall shape of the roots as shown in Fig. 1. The SCA creates a boundary volume, populates it with attractor points indicating potential growth space, and iteratively generates root branches while eliminating points. The flexibility of the defined boundary allows the model to replicate diverse root architectures characteristic of different species, such as tap, heart, or plate root systems. Moreover, in constrained environments like rocky terrains or urban areas, the shape of the defined envelope can be changed to restrict root expansion and simulate site-specific growth conditions realistically.

The radii of root branches are calculated starting from the tips, assuming an initial uniform radius, $\mathrm{r}_0 = 1$ which can be adjusted. all radii r are expressed in consistent length units, such as centimeters (cm). Higher-level branch radii are determined iteratively upward, combining the radii of contributing lower-level branches at each junction as follows:

$$\mathrm{r}^2 = \sum_{\mathrm{i}=1}^{\mathrm{k}} \mathrm{r}_\mathrm{i}^\alpha \qquad (1)$$

Where 2dαd3 and k represents the number of lower-order branches. In this study, $\alpha = 2$ corresponds to the cross-sectional area of the supporting branch, whichis equal to the sum of the cross-sectional areas of the contributing branches. Finally, the calculated radii are scaled to match the trunk's Diameter at its Breath Height.This stochastic process allows for realistic and adaptable modeling of root systems, which is particularly valuable given the limited data available from non-destructive testing of root geometries. The approach can accommodate constraints related, for example, to urban infrastructure.

The SCA-generated root geometry is integrated into a 3D FEM model in Plaxis 3D to simulate the mechanical response of the root-soil system under lateral static loads, such as wind effects. Root branches are represented as embedded beams with elastoplastic behavior. The soil is modeled as a homogeneous and isotropic porous medium following the principles of the Mohr-Coulomb failure criterion. A rigid plate matching the stem diameter is added to ensure realistic force transfer from the tree to the soil, preventing punch-through failure. The entire modeling process is automated using Python scripting.

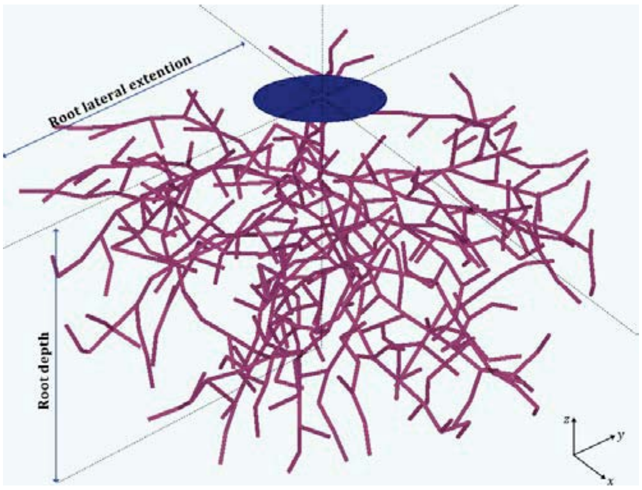

Fig. 1. Root-soil model geometry.

3. Results

This paper shows selected results pertaining to the parametric estimation of the overturning moment M, i.e., the moment required to induce overturning-type failure. The SCA was utilized to generate root systems with three different values of maximum lateral root extension (Fig. 2). Soil and root properties were taken as constant at all depths. However, each configuration was simulated 10 times using randomly distributed attraction points to account for uncertainties arising from varying root geometries. The soil was assigned a modulus of elasticity of 50 MPa, a cohesion of 5 kPa, a friction angle of 30°, and a Poisson's ratio of 0.3. Roots were assigned a modulus of elasticity of 1 GPa, an axial resistance of 1000 kN, and diameters scaled such that the largest root at the collar area measured 45 cm in diameter.

As shown in Fig. 2, Mincreases monotonically with root depth and root lateral extensions. For instance, a 25% increase was observed for root lateral extension of 1 m when the root depth increased from 0.5 to 2.5 meters, and this value decreased to 17% and 15% for root lateral extension of 1.5 and 2.0 m, respectively. The variation is shown in Fig. 2, along with the standard deviation of values obtained from 10 realizations for each root depth. Fig. 2 shows very low dispersion in the inter-realization relationship between root depth and overturning moment for 1m of lateral root extension (with standard deviations ranging from 3.1kNmto 5.7 kNm), while larger standard deviations were observed for the 1.5 m of extension (ranging from 9.3kNm to 11.7kNm), and for the 2 m of lateral extension varies (7.2kNm to 16.7kNm).

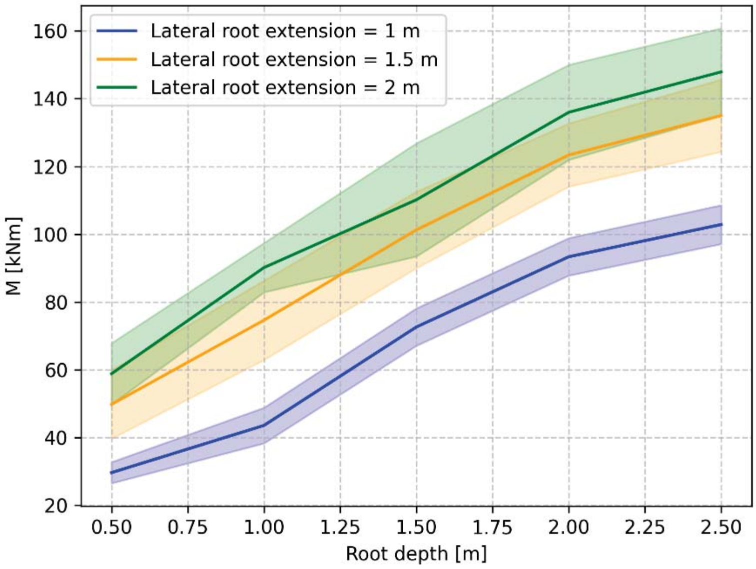

Fig. 2. Effect of the stochastic simulation of root geometry on relationship between root depth and maximum overturning moment for different root lateral extensions.

4. Conclusion

This paper provides selected results from a broader study aimed at highlighting the critical role of root geometry in defining the mechanical stability of trees under lateral loading. The combined use of a stochastic approach to the simulation of root geometry and numerical finite element modeling provides an effective framework for analyzing root-soil interactions. With respect to overturning failure, results indicate that deeper root systems and greater lateral root extension both significantly improve overturning resistance. Quantitative results can be interpreted critically. While deeper roots enhance resistance by anchoring the tree vertically, increased lateral extension provides additional lateral stability, leading to a greater maximum overturning moment. The coherency between numerical outputs and qualitative reasoning suggests that the proposed approach offers a robust tool for understanding tree anchorage mechanisms and can inform nature-based solutions for slope stability and erosion control in geotechnical and environmental engineering.To further evaluate the accuracy and applicability of the proposed model, future studies should focus on calibrating the parameters of SCAusing data from field experiments. Comparative analysis with experimental results will be essential to validate the model's predictive capability.

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