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Perspective

# Role of root morphological and architectural traits: Insights into root-inspired anchorage and foundation systems

Plant root systems, a crucial component of biogeotechnics, have been recognized as a promising and sustainable strategy to address novel challenges in geotechnical engineering, i.e., climate change (Ng et al., 2022). Root-soil composite and root-reinforced slopes have received widespread attention in recent decades, due to the ability of root to regulate soil properties through mechanical reinforcement and hydraulic transpiration (Li & Duan, 2023; Ni et al., 2024). Fig. 1 provides a co-occurrence network plot of plant root-based soil reinforcement strategies published over the last decade, where three clusters are identified with different colors. On the left of the network map, clusters in red and blue are primarily driven by geotechnical investigations of vegetated slopes (i.e., plant root reinforced slopes) and root-soil composite/root-permeated soils, as denoted by the terms like “model”, “test”, “slope”, “strength” and “vegetation”, while the green cluster on the right side demonstrates botany-related domains, for instance, “plant growth”. Indeed, the reinforcement of vegetated soil strength is complex and varies significantly with an abundance of factors, both mechanically and hydraulically. Particularly, the impact of root morphology and architecture cannot be negligible, including keywords “root area ratio”“root distribution”“root morphology”“root diameter”“root density” in Fig. 1 with the root size and root depth ranking foremost. Deep and coarse roots typically penetrate the entire failure plane and serves as anchorage elements, while shallow and fine roots interweave to form a dense mat (Li et al., 2023). Besides, parameters such as root branching pattern and root tortuosity (i.e., an indicator describing root path selection), which have rarely been discussed in the spotlight before, contribute to the understanding of the underlying load-transfer mechanism of the plant root system, and provide insights into the selection of vegetation types as well as root-inspired anchorage and foundation systems (Martinez et al., 2022; Zhang et al., 2023; Zhang et al., 2024).

Root morphological and architectural parameters can be categorized as dimensional parameters (root length, root diameter, root tortuosity, cross-sectional shape, surface roughness, etc.) and topological parameters (branching pattern, lateral orientation, root area ratio, etc.), where the later parameters emphasize the spatial distribution and connectivity of root systems (Fan & Chen, 2010; Ghestem et al., 2014; Mickovski et al., 2007; Reubens et al., 2007). Generally, the effects of architectural parameters are primarily appropriate for evaluating coarse roots systems, whereas the membrane-like finer roots tend to serve as nutrient and water absorbers (Stokes et al., 2009). In fact, the classification criteria regarding different root architecture still lacks, and exsiting classifications are mainly based on the spatial distribution of root systems, for instances, taproot, fibrous, plate root systems in Mallett (2019); H-type, R-type, CH-type, V-type, M-type and W-type in Li et al. (2016) and Wang et al. (2020); uniform, triangular, exponential, parabolic root systems in Ng et al. (2015). Despite the variations in nomenclature, there are certain resemblances, e.g., the V-type and taproot root systems are both characterized by coarse, near-vertical roots, and H-type, plate and exponential types by horizontally-extended roots, and fibrous and R-type by oblique roots that are uniformly dispersed around the perimeter.

The architectural effect varies under different loading scenarios. Taproot and fibrous root systems are considered the most resistant to vertical pullout, with taproot length and number of lateral roots being the primary contributors (Zhai et al., 2024). Longer root lengths result in larger root-soil contact area, which mobilizes greater shearing stresses (Zhu et al., 2023), and lateral branching along the root length significantly increases pullout capacity due to greater bearing area and volume of soil to be uplifted (Burrall et al., 2020). In addition, branching inclination and number of laterals do have a considerable effect on pullout performance, as the pullout mechanism of inclined branches and nearly horizontal roots vary, with intermediate branching angle having the highest pullout capacity (Zhu et al., 2023; Mallett et al., 2018). The effect of the number of laterals is related to soil arching phenomenon (Mallett, 2019).

Asymmetry in radial distribution of roots have adversely impacted performance in vertical pullout (Burrall et al., 2020), but are potentially more beneficial under overturning loads (Galli et al., 2023), on the premise that the plate type is more suitable for overturning resistance compared to fibrous and taproot root systems. Root morphological traits are even more essential than mechanical parameters in overturning capacity (Yang et al., 2017), particularly the presence of horizontal roots along the loading direction (Zhang et al., 2020; Zhang et al., 2022).

The additional shear strength in the mechanical reinforcement of vegetated slopes derives from the taproot that crosses the slip surface (Liang et al., 2017), and the angle between the two contributes to the shear strength (Li et al., 2021). R-type root systems are identified as the most effective against shearing in soil (Fan & Chen, 2010; Li et al., 2016; Wang et al., 2020), fibrous roots are suitable for stabilizing sandy slopes (Nomleni et al., 2023) and increasing stability of upper slopes (Song & Tan, 2024). For the mechanical strengthening by fine roots, root distribution and root orientation relative to shearing direction contribute most to the root-soil composite (Jiang et al., 2022; Karimzadeh et al., 2022; Zhang et al., 2010). In terms of hydraulics, exponential and triangular root systems are capable of generating higher negative pore water pressure and transpiration-induced suction due to the additional soil-root

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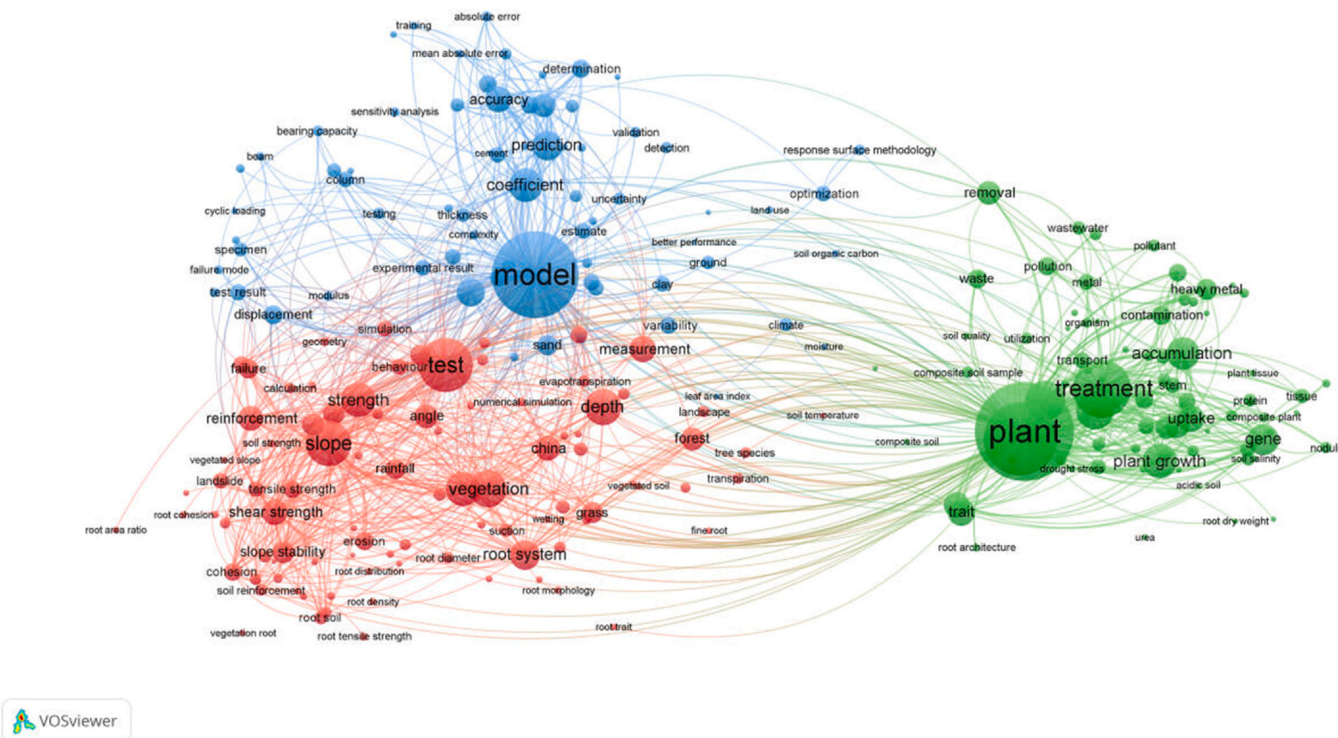


**Fig. 1.** VOSviewer co-occurrence map of plant root-based soil mitigation strategy.

contact area (Liang et al., 2017; Ng et al., 2015, 2016; Zhu et al., 2018). Certainly, root density and root diameter can likewise contribute to the hydraulic properties (Lu et al., 2020), however there is relatively less investigations on the hydraulic effects of root tortuosity and branching point, which will be of interest in future endeavors.

Understanding the effect of root tortuosity on root-soil interaction is crucial not only because of its notable impact on predicting mechanical responses and load transfer mechanism within individual root systems (Schwarz et al., 2011), but also due to the fact that models incorporated with root tortuosity are an important means by which geotechnical components approximate the real root systems. However, current investigations on roots with tortuosity are very limited. Ding et al. (2024) conducted pullout test on 3D-printing roots with tortuosity, the tooth ribs along the tortuous roots strongly engaged with the surrounding soil and therefore dramatically increased the pullout capacity, denoting a totally distinct root-soil interaction from that of the straight root, while somewhat analogous to that of the snakeskin-inspired surfaces (O'Hara & Martinez, 2020; Zhong et al., 2021). Equally, modellings of tortuous roots are also rare, including frameworks based on L-system enabling gravitropism root growth with tortuosity by Schnepf et al. (2018) and Xu et al. (2021), and molecular simulations using elongated tubes by Fakih et al. (2019).

Root morphological and architectural traits can shed light on root-inspired anchorage and foundation systems, since this is the priority when designing root bionic elements. Undoubtedly, lateral branching significantly increases bearing capacity of traditional geotechnical components, but there is an upper limit to the effect of the number of branches (Ads et al., 2023). Increasing the structural complexity, e.g., by increasing the number of branches and altering the flexural properties, can optimize the pullout resistance until a certain limit is reached, but weaken the anchorage performance beyond that limit (Kim et al., 2023). There is a tradeoff between approximating the real root systems and the anchorage performance of root-inspired systems, and thus an urgent need to determine the crucial parameters affecting the load transfer mechanism (Houette et al., 2023; Shrestha & Ravichandran, 2020). At present, there is not an individual parameter that comprehensively characterizes the root-inspired systems, integrating both morphological and architectural traits, which will be one of the priorities of future endeavors.

## CRediT authorship contribution statement

**Wengang Zhang:** Writing – review & editing, Supervision, Conceptualization. **Ruijie Huang:** Writing – original draft. **Jiaying Xiang:** Writing – original draft. **Ningning Zhang:** Writing – review & editing, Supervision. **Matteo Oryem Ciantia:** Writing – review & editing, Supervision. **Leilei Liu:** Writing – review & editing. **Jian Yin:** Writing – review & editing. **Changbing Qin:** Writing – review & editing.

## Declaration of Competing Interest

The author declare the following financial interests/personal relationships which may be considered as potential competing interests: Ningning Zhang is employed by Ramboll, which may be considered as potential competing interests, and other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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