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A micromechanical study of root-soil interaction: growth patterns and pullout resistance

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ABSTRACT: Understanding root-soil interaction is inherently challenging due to the difficulty in visualizing and measuring the physical processes that govern root anchorage below ground. A robust understanding of these mechanisms is essential for developing reliable models to quantify root pullout strength. Traditionally, root-soil reinforcement has been modelled as an equivalent homogeneous medium, which overlooks potentially important local variations in soil and root structure. To address this limitation, this study incorporates the geotropic behaviour of root growth and its tendency to follow paths of least resistance, using the Discrete Element Method (DEM). A novel DEM composite root-soil model is presented and, by simulating root growth into the soil followed by pullout tests, the pullout strength of various root systems is evaluated. The DEM model accounts for both the characteristics of root growth and branching and the mechanical interactions between roots and soil, providing a novel approach to investigating root pullout behaviour. Simulation results indicate that physical properties such as root diameter, density, and strength significantly influence bending during growth, which in turn affects pullout resistance. This research offers new insights into root-soil interaction and has important implications for engineering applications such as slope stabilization.

Keywords: Root-soil interaction; Discrete element method; Pullout test

1 INTRODUCTION

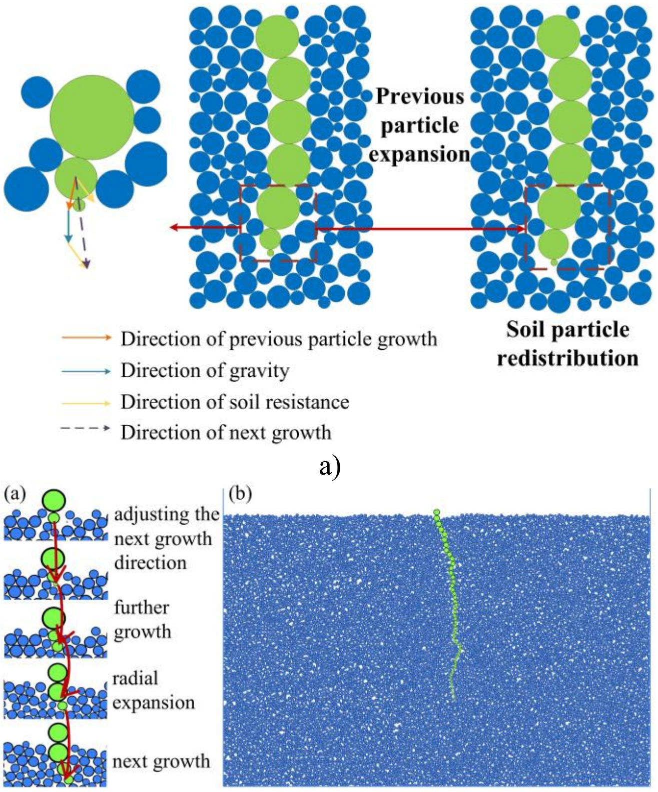
In contemporary settings, geohazards from exposed slopes—amplified by infrastructure expansion and more frequent extreme weather—pose serious risks to mountain communities and ecosystems, causing casualties and economic loss. Vegetation-based slope protection, as a bioengineering measure, has proved effective in enhancing stability and reducing surface erosion (Boldrin et al., 2021; Ni et al., 2020; Zhang et al 2025). Yet practice has outpaced theory because root morphology, spatial distribution and hydro-mechanical coupling are complex; without robust analysis, the full potential of these solutions remains under-realised. This study therefore examines the root–soil composite and its contribution to slope strength and stability.

Research on root-soil shear strength has concentrated on individual influencing factors, such as (i) Root species, (ii) Root morphologies, (iii) Root content, length, and diameter, (iv) Soil water content, and (v) Soil particle size. While these studies provide valuable insights, most focus on root properties, with limited attention to soil characteristics.

Numerical simulation offers a promising way to study root-soil interactions during growth. While FEM often oversimplifies root trajectories and grain-scale interactions (Calusi et al., 2020; Mickovski et al., 2011), DEM captures root-soil contact, rearrangement and large displacements (Ciantia et al., 2016) and has succeeded in modelling penetration problems (Chen et al., 2023; Ciantia et al., 2019; Zhang et al., 2023). Recent DEM studies include root tension/bending, adhesion, interface friction (Bourrier et al., 2013; Fakih et al., 2019) and rigid root soil interaction investigating scaling effects (Zhang et al 2024) but typically neglect radial thickening and coordinated, multi-level growth. Here DEM is used to model root growth in granular media, including radial root expansion and tip autonomous direction, yielding more realistic root–soil interaction and providing guidance for bio-inspired geotechnical design.

2 DEM ROOT GROWTH ALGORITHM AND MODEL ESTABLISHMENT

Roots penetrate the soil to anchor plants and acquire water and nutrients. During branching and elongation, they adapt to heterogeneous environments through diameter adjustment, architectural change and secretion of mucilage (Popova et al., 2016). These adaptive behaviours modify the surrounding soil and affect the mechanical behaviour of root-soil composites. Modelling this approach enables a better understanding of the different growth forms of roots in the same soil type or the same type of roots in different soils, thus elucidating their impact on the strength of root-soil complexes.



a)

b)

Figure 1. a) Root growth autonomous direction algorithm diagram and b) schematic of root particle growth process along with a full view of a root-soil composite DEM model

2.1 *Simplifying root growth drivers*

Given the complexity of root growth, this study distils the factors influencing root growth direction into three governing forces: gravity, soil resistance, and growth force. Gravity drives downward penetration, ensuring stability and access to deeper resources. Soil resistance deflects roots towards paths of lower mechanical impedance, representing the natural search for less compact zones. Growth force, the internal pressure generated by the root, enables penetration through local obstacles. The balance among these forces reproduces natural adaptability: gravity provides a steady downward bias, while soil resistance and growth force interact dynamically, steering the root through heterogeneous soils. This framework forms the basis of an autonomous root growth algorithm reflecting real root tropism and flexibility.

2.2 *Developing the root growth algorithm*

The DEM-based root growth algorithm is implemented using chains of spherical particles that can radially expand with root growth. Each particle segment enlarges sequentially, displacing and rearranging surrounding soil particles to form new growth space. The model couples the three forces described above to determine the next growth direction: gravity maintains vertical orientation, soil resistance guides the root towards weaker zones, and growth force overcomes local resistance. Figure 1 illustrates the conceptual scheme to model root growth in DEM. The model enables adaptive, stepwise root development, reliably reproducing the interactions between root expansion and soil deformation observed in natural systems (Hou et al. 2022).

2.3 *A lab scale root-soil interaction model*

To capture the complex mechanics of root–soil interaction, distinct contact models were assigned to different particle groups. Root–soil and soil–soil contacts adopt the linear rolling-resistance model, which accounts for rotational resistance and ensures stable particle motion without extra damping. Root–root contacts use the linear parallel-bond model, enabling transmission of forces and moments until bond rupture, realistically representing roots that, once broken, do not reconnect. Together, these models reproduce the resilient yet brittle behaviour of real roots embedded in soil.

The numerical domain (0.6 m × 0.4 m rigid box) was selected to limit boundary effects. Soil particles (0.15–0.25 cm, density = 1.8 g cm^{-3}, porosity = 0.20) were generated in layers. Because the simulated root-to-particle size ratio is smaller than in nature, slightly larger soil particles were used to balance realism and computational cost, acknowledging minor scale effects on displacement and stress fields.

Root growth was implemented as a dynamic, stepwise process (Figure 2a):

(i) Initialisation: root coordinates and initial growth angle were defined by input parameters such as diameter and decline rate.

(ii) Growth-angle calculation: a function was used to evaluate local contacts and total soil resistance, combining it with gravity and the previous segment force to determine the new direction.

(iii) Segment placement: next particle position was computed from the preceding segment geometry.

(iv) Radial expansion: each segment initially expanded to half of its diameter, then gradually to full size via a radial expansion routine that displaced nearby soil particles. This mechanism simulates the creation of growth space and local compaction observed in laboratory experiments.

2.4 Model validation

To verify the DEM model, numerical shear and pull-out tests were performed to replicate the laboratory experiments on root–soil composites (Figure 2b, c). The shear box geometry and particle parameters (soil 0.15-0.25 cm; root 10 mm, tensile strength = 10 MPa) were kept identical to the physical tests, ensuring consistency between simulation and experiment. This setup allows direct assessment of the model's ability to reproduce the mechanical response and failure mechanisms of root-reinforced soils.

The simulated results showed excellent agreement with experimental data. The predicted pull-out strength (9.21 MPa) and shear stress–strain curves matched measured values, both exhibiting sliding-out failure and similar post-peak behaviour. The model successfully reproduced upward root movement and interfacial sliding during shearing, confirming its capability to capture the coupled tensile and shear responses that govern root–soil reinforcement.

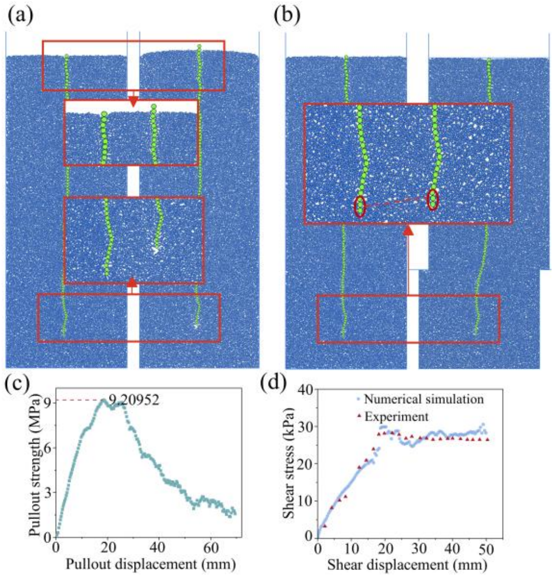


Figure 2. (a) Simulation process of pull-out test and (b) shear test; Simulation curve of (c) pull-out test and (d) shear test

3 ROOT-SOIL INTERACTION

Most studies on root–soil composites emphasise root traits, whereas the mechanical interactions between roots and soil, as well as the influence of soil properties, remain insufficiently explored. Using the DEM, this study quantifies root-induced soil compaction and stress redistribution at particle scale. The model tracks local porosity and stress variations as roots grow and expand, enabling detailed observation of the affected zone while minimising boundary effects.

3.1 Effects of root systems

To investigate how root morphology affects soil behaviour, the DEM simulations systematically varied root particle size, length, and effective modulus. The effects of root growth were quantified using the ratio of porosity reduction to initial porosity to represent compaction, and the ratio of final to initial stress to evaluate stress increase. These dimensionless indices minimise bias from initial soil conditions and allow direct comparison of different growth patterns.

The results show that root geometry strongly controls soil response. Thicker roots displace more soil (Figure 3), producing greater porosity reduction and stress increase until a critical radius is reached, beyond which upward soil heave reduces efficiency (Figure 4a). Increasing the effective modulus (Figure 4b) leads to straighter trajectories and slightly stronger compaction, though its impact is less pronounced than that of size and length. Overall, an optimal combination of root dimensions and stiffness maximises soil compaction efficiency without inducing excessive deformation.

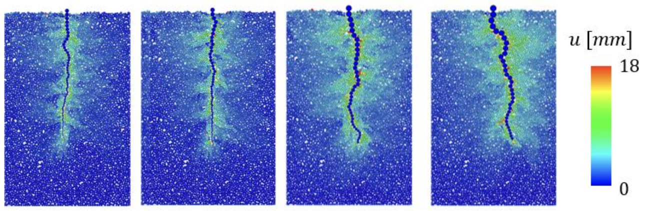


Figure 3. Contours of soil displacement for varying root thickness models

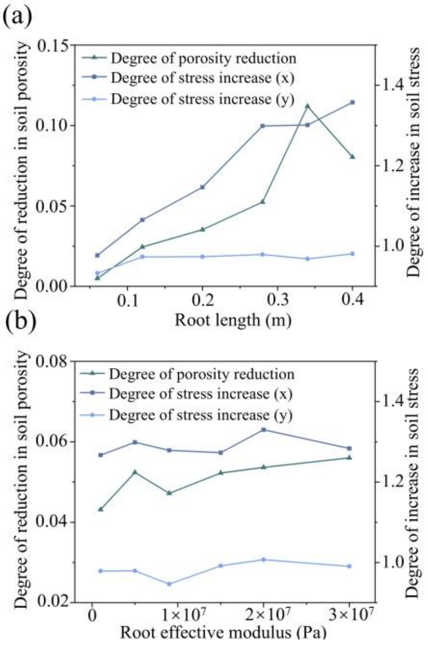


Figure 4. Effects of root a) length and b) effective modulus on pore reduction, and stress increase

3.2 Effects of soil properties

Beyond root morphology, soil properties, particularly particle size, porosity, and stiffness, strongly influence root growth and soil compaction. The simulations (Figure 5) show that larger soil particles, despite constant overall porosity, create wider pores that facilitate deeper root penetration and stronger compaction, whereas smaller particles restrict expansion and reduce efficiency. Increasing soil porosity enhances root growth and stress variation, as looser structures allow greater particle displacement during expansion. Together, these results demonstrate that soil fabric critically governs both the geometry of root growth and the magnitude of root-induced reinforcement.

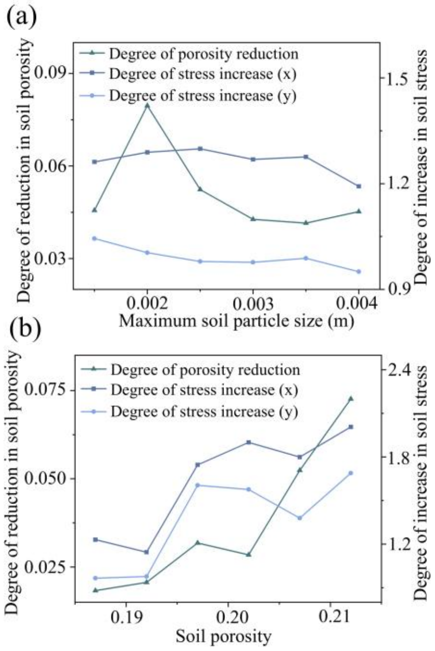


Figure 5. Effects of a) soil particle size and b) soil pore reduction on stress increase.

4 CONCLUSIONS

A DEM framework to simulate root growth and its mechanical interaction with soil is proposed. The model reproduces realistic root trajectories, radial expansion, and soil particle rearrangement, providing a particle-scale understanding of how roots compact and strengthen the surrounding soil. It offers a robust basis for analysing the micro-mechanical processes underlying root-reinforced geomaterials. Simulation results highlight that both root morphology and soil properties jointly control root-induced compaction and stress evolution. Optimising root geometry and soil fabric is therefore key to maximising reinforcement efficiency. Future work will extend the model to incorporate branching for more realistic root architectures and to conduct detailed pull-out and shear test analyses on root–soil composites.

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