Root-Soil Mechanical Interaction

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ABSTRACT: Roots growth in granular materials resembles the formation of open-mode discontinuities driven by the invasion of an immiscible phase. The root-soil interaction is studied in this work by means of complementary full field measurement techniques based on X-Ray Computer Tomography and finite element numerical simulations. High resolution X-Ray images captured the root tip geometry in detail and an analytical function was fitted to describe the root shape. Numerical simulations provided the evolution of the stress and strain fields in the soil around a root-shaped object as it swelled in the soil mass. These analyses show that the increase in the root internal pressure creates a zone of unloading and expansion ahead of the root tip, which facilitates cell multiplication at the root tip resulting in root growth.

INTRODUCTION

Plants influence the properties of soils; conversely, soil properties contribute to the natural selection of plants and their growth habits. Root growth is mainly regulated by grain size and pore geometry (they reflect the formation history of the soil), and alters the stress and strain field in the soil mass (Hiettiaratchi, 1990).

Root growth involves cell splitting and expansion (Gregory, 2006). Cell expansion occurs when the internal hydrostatic pressure (Turgor pressure) acting through the cell wall properties prevails over the constraints imposed by the cell walls and the soil external pressure (Greacen and Oh, 1972; Atwell and Newsome, 1990; Rygol and Zimmerman, 1990, Lew, 1996; Bengough et al. 1997). The wall pressure varies between the radial and longitudinal directions (Gill and Bolt,1955; Taylor and Ratliff,1969; Mistra et al,1986; Dexter 1987). The radial pressure is applied on a larger area and exerts a larger effect (Atwell 1993).

The swelling of the root tip creates a zone of radial stress release ahead of the root tip when the radial stress overcomes the soil pressure (Abdalla et al., 1969). When the soil strength impedes axial root growth, the root cap switches to radial growth, which leads to thickening (the stress for spherical cavity expansion in a soil is greater than for cylindrical expansion, i.e., the root - Hiettiaratchi, 1990; Nguyen, 1977; Vesic, 1972).

The relationship between cylindrical swelling and the stress release at the root tip has been experimentally and numerically explored (Atwell, 1988; Materechera et al, 1991; Wilson et al, 1977; Misra et al., 1986; Stolzy and Barley, 1968; Whiteley et al., 1981; Clark et al., 2008; Kirby and Bengough, 2002).

The purpose of this study is to identify mechanisms and processes ahead of the root tip that explain root growth in soils. Experimental and numerical methods are combined to investigate root-soil interaction.

EXPERIMENTAL STUDY

Air-dried homogeneous sand was wetted and poured into plastic containers (24mm internal diameter, 60 mm high). Specimens were scanned using the X-Ray CT Scan at LAB3S-R in Grenoble. The ImageJ software package was then used to for data post-processing to gather precise measurements of the root geometry (Figure 1).

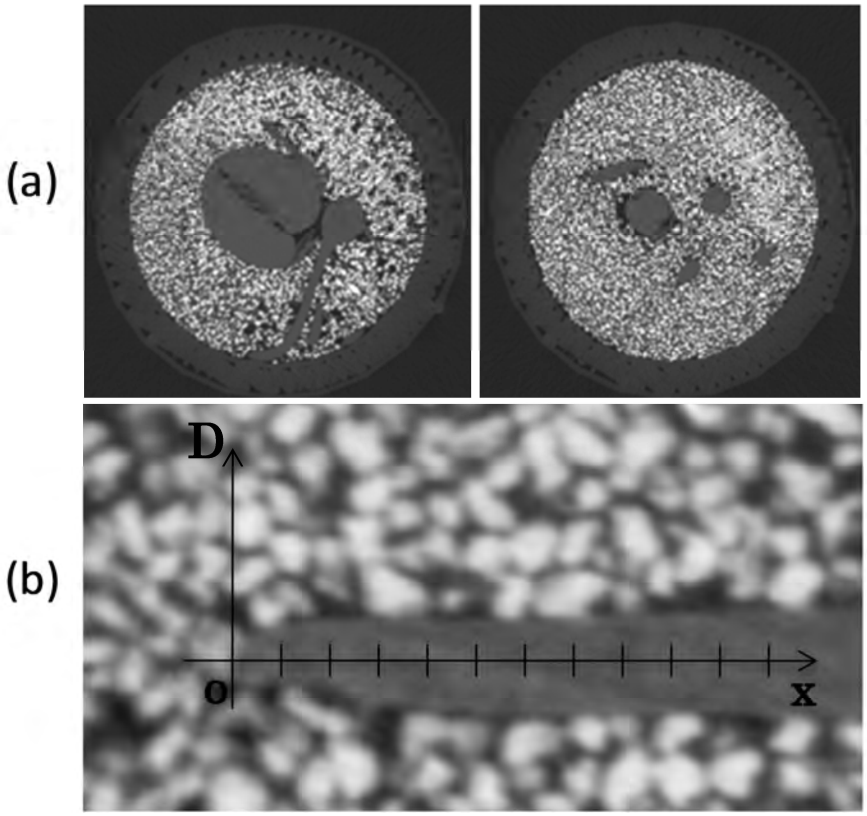

Figure 1: Root-soil interaction. High resolution tomographic images. (a) Two slices of tomograms obtained using X-ray CT scan. Roots (low density) appear as darker zones containing surrounded by white soil particles. (b) cross section along the root length to measure the root diameter as a function of distance from the root tip.

The root diameter vs. distance from the root tip was measured using tomographic images gathered at different stages of germination (voxel size: 34μm).The root diameter increases rapidly from D=0 to a value $D=D_c$ that depends on the degree of compaction of the soil. The length of this "root tip zone" x_{dc} is about 2.3 mm, while the average value found for D_c is about 0.7mm, hence $x_{dc} \sim 3D_c$ (Figure 2). The diameter at a distance x from the root tip follows the following trend

$$D(x) = D_c \cdot (1 - e^{-x})^{0.5} \tag{1}$$

where D_c is the mean value of the diameter outside of the root cap. (For comparison, refer to Bengough 1996 who plotted root diameter vs. distance from the root tip for pea roots in both loose 1.0 g/cm^3 and compacted 1.6 g/cm^3 sandy loam – that study had resolution limitations).

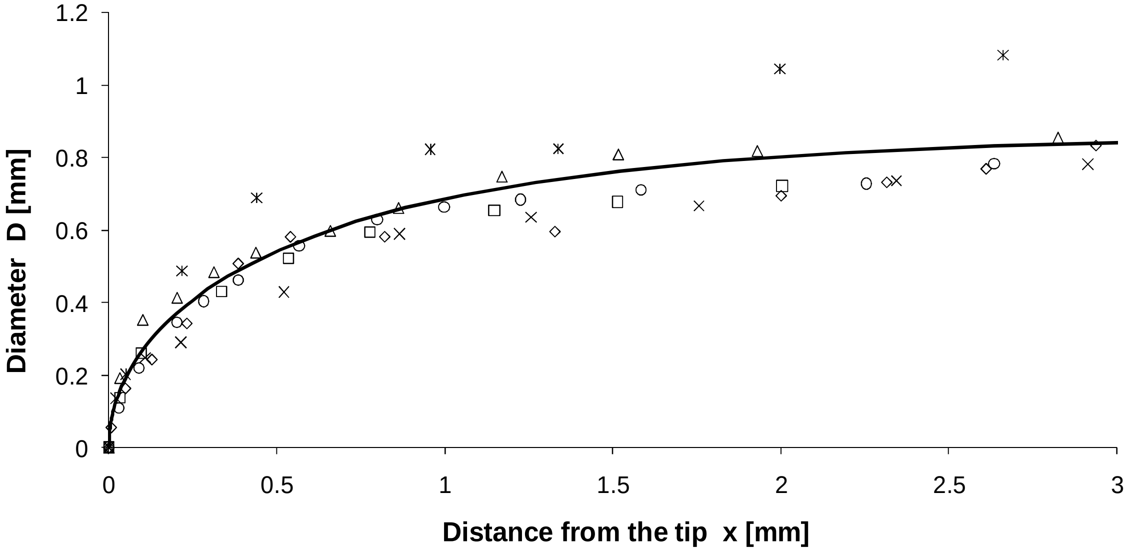

Figure 2: Root geometry from high resolution slices taken along the root

NUMERICAL STUDY

The finite-element method was used to model root penetration (Comsol Multiphysics 4.0). The soil was modeled as an elasto-plastic material, characterized by perfect plasticity and associated flow (Drucker-Prager Yield Criterion. Mesh: 2D axisymmetric, triangular 3-nodal elements with high element density around the root tip. Soil: friction angle $\phi=30°$; elastic modulus E=3.25 MPa; Poisson ratio $\nu=0.3$). The root is modeled using the measured geometry, and root penetration was simulated by applying an internal pressure normal to the root-soil interface (Figure 3). All the analysis is conducted in terms of effective stress.

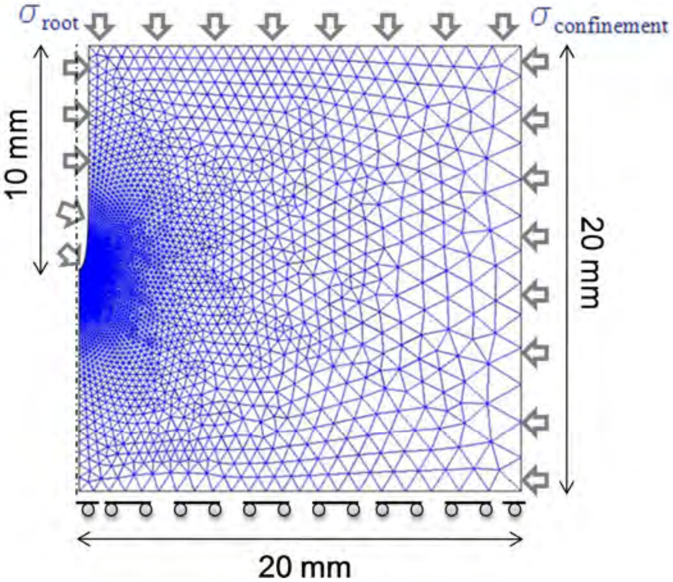

Figure 3: Numerical simulation. FEM mesh and boundary conditions.

The predicted mean stresses and volumetric strains in the zone near the root tip are shown in Figure 4. The soil mass experiences a radial stress release in the immediate vicinity of the root tip due to the internal radial pressure of the root (Figure 4b); the medium remains in compression everywhere. The radial stress at the root tip is almost half that of the boundary pressure (1 kPa). Higher stresses are observed along the root-soil interface as the root pushes against the soil.

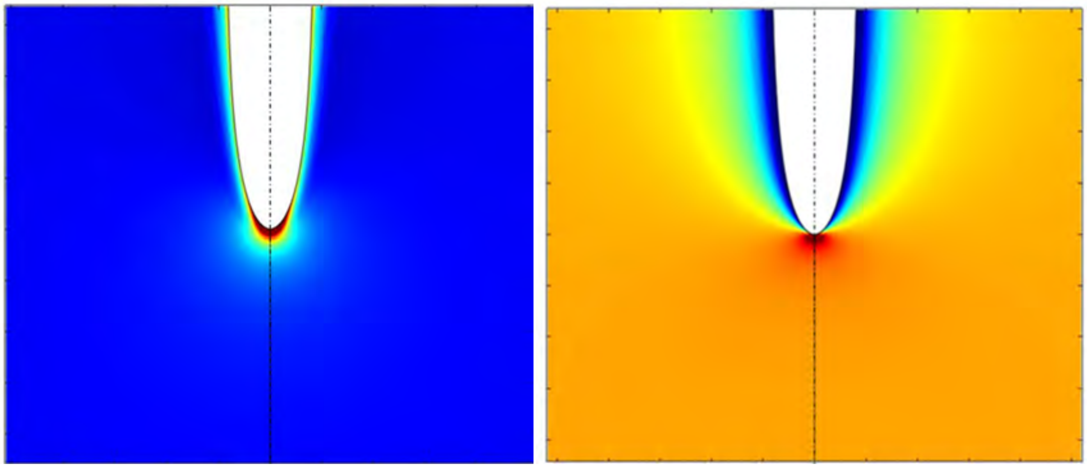

Figure 4: Numerical results. (a) Volumetric strain field: the soil dilates around the root tip as the root swells. (b) Radial stress field: The soil is in compression everywhere but there is a stress release at the root tip as the root swells.

DISCUSSION

Results show that root growth in soils takes place as an “open mode discontinuity” much alike hydraulic fractures driven by the invasion of an immiscible phase and desiccation cracks (Shin and Santamarina 2010, 2011). Indeed, the forces applied against soil grains resemble forced gas invasion into water-saturated sediments or ice lenses formation. However, the geometry of the evolving discontinuity is different in both cases (root rounded shape vs. ice blade-shape) and affects growth.

The plot in Figure 5 shows the evolution of the radial stress along the root axis ahead of the root tip. The maximum stress release occurs exactly at the root tip, and the magnitude is proportional to the root internal pressure. For the elastoplastic simulation, the point of maximum unloading is slightly below the root tip. The cohesionless nature of the soil model does not allow for tensile stress, in other words, root growth does not involve a tensile fracture.

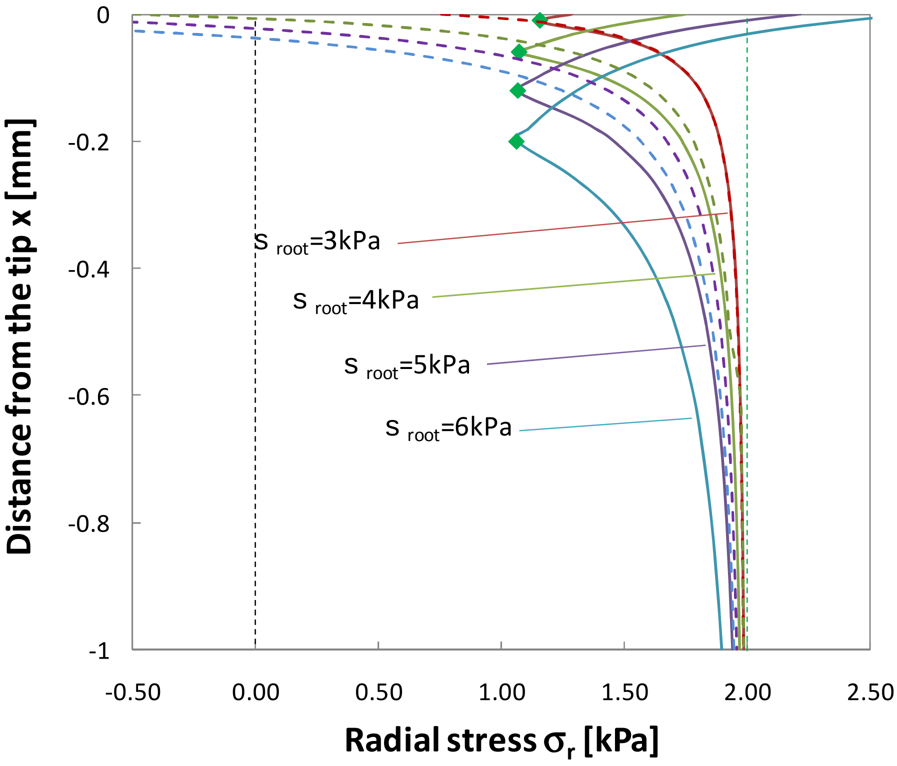

Figure 5: Numerical results. Radial stress in the soil mass ahead of the root tip for different values of the root internal pressure. Elastic simulation (dotted lines): the maximum stress release occurs exactly at the root tip. Elasto-plastic simulation (continuous lines): the higher the root internal pressure, the further from the root tip is the point of maximum unloading.

When the root internal pressure overcomes the confinement pressure of the soil, the stress at the root tip can be related to the confining pressure as

$$\beta = \frac{\Delta\varepsilon}{\Delta\sigma / E} \tag{2}$$

Figure 6 shows that the stress factor β is constant for the elastic simulation, whereas it increases as the internal pressure increases for the elastoplastic case. Unloading and expansion at the root tip and the associated increase in porosity allow root cell splitting and root growth. On the other hand, the soil is consolidating along the root-soil interface because the osmotic suction imposed by the root (Krahn and Fredlund, 1971; Sudhakar and Shivananda, 2005).

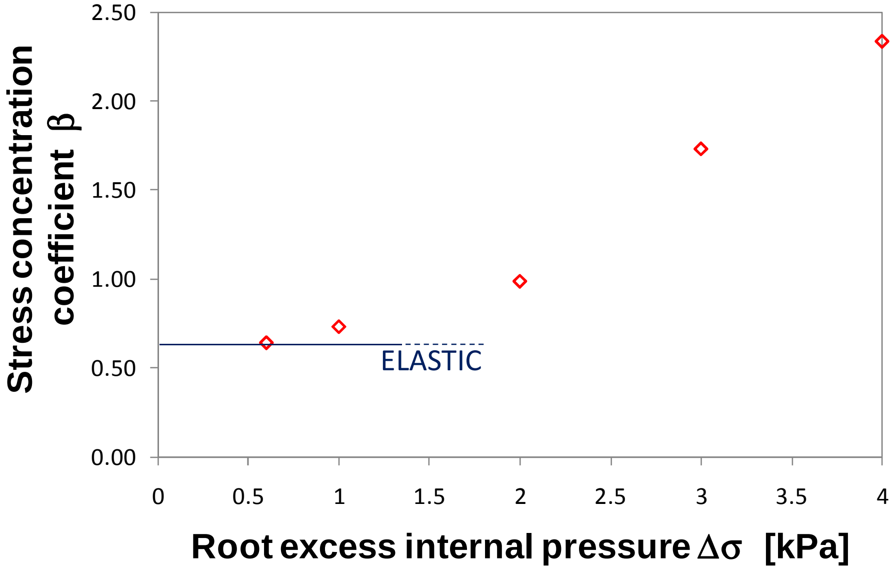

Figure 6: Stress concentration at the root tip. The higher the root excess internal pressure, the higher the stress localization at the root tip.

CONCLUSIONS

High resolution X-Ray tomograms permit a detailed geometric analysis of root characteristics and processes. The shape analysis of buried roots reveals a common root shape pattern for the plants examined in this study.

Elongation and radial expansion are related to mechanical conditions at the root tip: difficult invasion conditions promote the radial expansion of the root before the root tip advances further into the “weakened” soil mass ahead of the root tip. There is also an increase in porosity and pore size ahead of the root tip during unloading and expansion. The root shape plays a fundamental role in determining the intensity of these mechanisms.

A stress and strain analysis around an advancing root using finite-element simulations reveals an effective stress compatible interpretation of root growth in the form of open-mode discontinuities.

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