Root-reinforced sand: kinematic response of the soil

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Abstract. . The influence of the soil on the growth of a root system has been largely investigated. By contrast, the aim of this work is to go deep into the details of how the soil may be influenced by the root system. In particular, the root growth process and its potential to improve the soil strength is explored. Even though roots can be seen as fiber-like reinforcements, their growth changes the soil microstructure. Consequently, one of the objectives is to understand how the water content and the soil displacement fields evolve when an inclusion expands radially and axially. In particular, an investigation was carried on to characterise the deformation of the solid phase of the soil, due to the root growth. A series of in-vivo x-ray tomographies was acquired with Maize seeds growing roots into a coarse Hostun HN1.5-2 sand. Digital Image Correlation is used to calculate the soil 3D displacement fields around the growing plant roots.

1. Introduction

Plants represent 99 % of the Earth biomass. Root-soil interactions greatly influence soil formation and erosion, together with soil mechanical and hydraulic properties. Effects of soil properties on root growth have been widely studied. A method for quantifying root-macropore associations from horizontal soil sections is illustrated in [1], where it was shown that root growth in arable soils is often limited by soil strength [2], [3], or by the availability of macropores that provide low-resistance pathways for root growth in very strong soils [4]. More recently, the effect of root hairs has been studied. They have a key role in anchoring the root tip during soil penetration [5].

The aim of this work is to investigate which soil properties are altered when a root element grows, *i.e.*, looking at the same process from the point of view of the soil. X-ray tomography is a promising non-destructive method, allowing a time-series of 3D volumes to be acquired. This technique has been extensively used in soil science, to understand the response of the Root System Architecture (RSA) to the soil texture [6] and to visualize the root system itself [7]. This paper presents the methodology used to create samples composed by a granular soil and plant roots. Through this specific protocol, reproducible samples are analysed through x-ray tomography. A detailed identification of each phase in the sample is performed, leading to the qualitative description of the evolution of the structure, and the quantitative study of the kinematics of the system.

2. Materials and Methods

2.1 Sample preparation

A specific protocol was followed to prepare the specimens used for the experiment, in order to obtain reproducible cylindrical samples. In this study, a coarse Hostun sand (namely HN1.5-2) [8] with D_{50}= 1.5mm [Fig.1] was pluviated into cylindrical transparent Perspex pipes (5 cm in diameter and 10 cm in height). The pluviation was done with a controlled drop height, with the objective to obtain a reproducible dry bulk density (1.69 g/cm^3). A germinated maize seed was placed in the upper part of the sample, during sand pluviation. The water content of the sample (0.1g/g), was chosen to optimise seedling growth [9]. Nutrients were added as required to sustain good growth.

2.2 Image acquisition

X-ray tomographies allow a detail image to be acquired, of both the root system and the sand particles. The tomographies are taken with a time lapse of 24 hours throughout 7 days. Each scan lasts less than 2 hours, with a

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pixel size of 40 µm/px. Given the dimensions of the sample and the setup of the machine [Fig.2], this was the highest reachable pixel size.
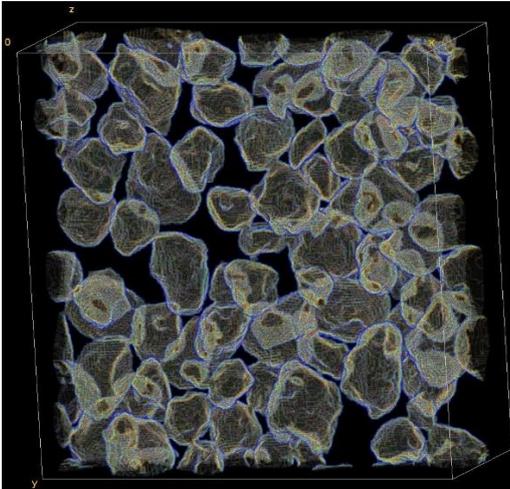
Fig.1. 3D representation of a sub-volume (250 x 250 x 50 pixel) extracted from the whole sample, showing the morphology of the Hostun sand grains. The pixel size of the image is 40 µm/px.
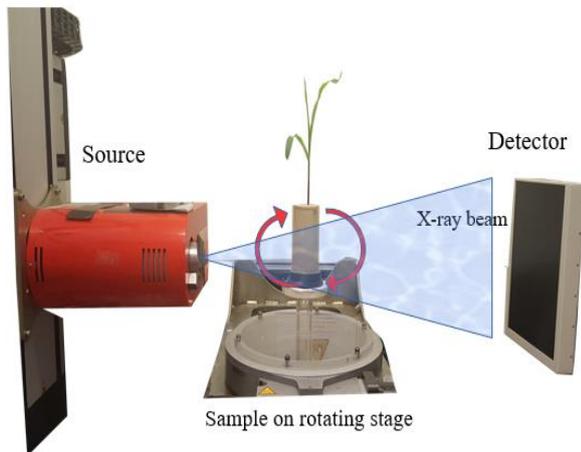
Fig.2. X-ray micro tomography set-up used to image the root-soil systems in a cylindrical specimen. The sample is placed on a rotation table and the distance between the x-ray source, the sample and the detector was fixed throughout the whole observation.

The main components of the maize root system [10] develop over a week, hence the sample is scanned for 7 days. The one week old root system is composed of embryonic primary and seminal roots of post embryonically formed crown root and lateral roots. Fig. 3 shows the daily progress of the root system inside the sand specimen.

Fig. 3. 3D rendering of the daily root development.

3. Analysis

3.1 Phase identification

A new image processing technique was developed to identify each phase of the specimen, *i.e.,* sand grains, plant roots, pore water and pore air.

We started by excluding the outside of the sample from the analysis. With a combination of thresholding and denoising filters, to smooth images while preserving edges, sand grains were identified. Root voxels are separated from the rest of the matrix, according to their grey values. That way, the seed time evolution could be established. Note that root and water grey values are very close, so the small volumes of pore water are recognized as root phase, in a volume where the root selection is removed. Once that the grains and root have been determined, the identification of the air, is easy, since it has a grey values range that does not belong to the other elements in the system.

Accuracy of the phase volumes obtained by image analysis after day 0 are compared against the volume fractions of water and sand introduced in the medium. After day 0, segmentation parameters were kept identical for further images analysis (corresponding to the following days).

A typical result of the phase segmentation, is shown in Fig.4. Each phase is defined with a different colour detailed in the legend.

3.2 Displacement field

Both continuous displacement fields and discrete (*i.e.,* grain-based) displacement fields of the sand solid phase are measured with image correlation.
We focus here on the discrete displacement fields representing the translation and the rotation of the centre of mass of each sand grain. The discrete displacement fields are computed from the labelled image of the sand matrix by application of discrete digital image correlations (discrete

DIC). Labelled images, to identify each grain of the sand sample, are obtained by using a 3D watershed algorithm applied on the segmented grain phase to separate touching grains.

The discrete DIC is performed with an image processing code dedicated to granular materials [11]. The configuration of the root-soil system at day 0 (*i.e.*, the day when the germinated seed was placed in the specimen) is used as the reference configuration, for the reason that the root was not able to cross the soil yet. Hence, total discrete displacement fields are computed between different time configurations (day 0 and day 2, day 0 and day 3, ., up to day 0 and day 6). The maps showing the vertical (Z axis) and horizontal (Y axis) displacements of the sand particles at different times are shown in Fig.5 in horizontal and vertical slices, respectively. The parts of the roots included in those sections are displayed in green.
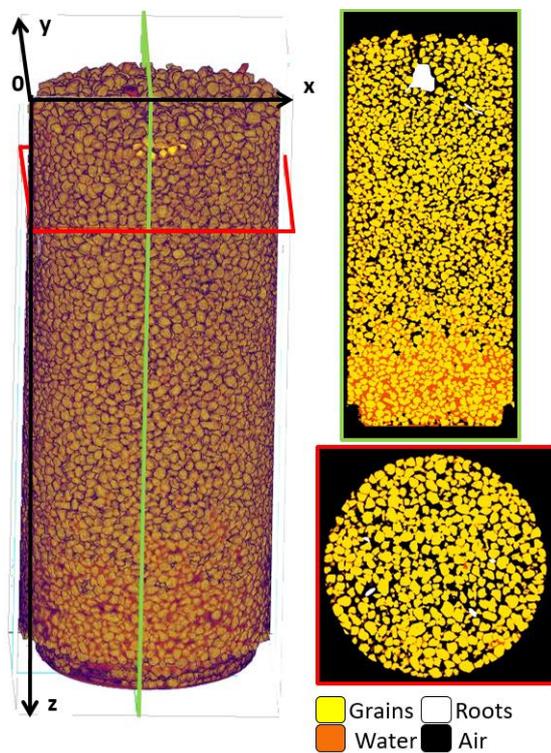

Fig.4. 3D sample volume and identification of the phases in vertical and horizontal slices.

4. Results

As a first step, the investigation focuses on the sand grains in direct contact with the roots which are the most prone, a priori, to move during root growth. Formerly, the root structure at the last day of observation (day 6) is characterised, consequently, the sand particles at the surface of the final root system are selected, as shown in Fig.6.

In total, we analyse 1004 out of 32000 particles present in the specimen. The origin of the axes is placed at the top of the sample [Fig.4].
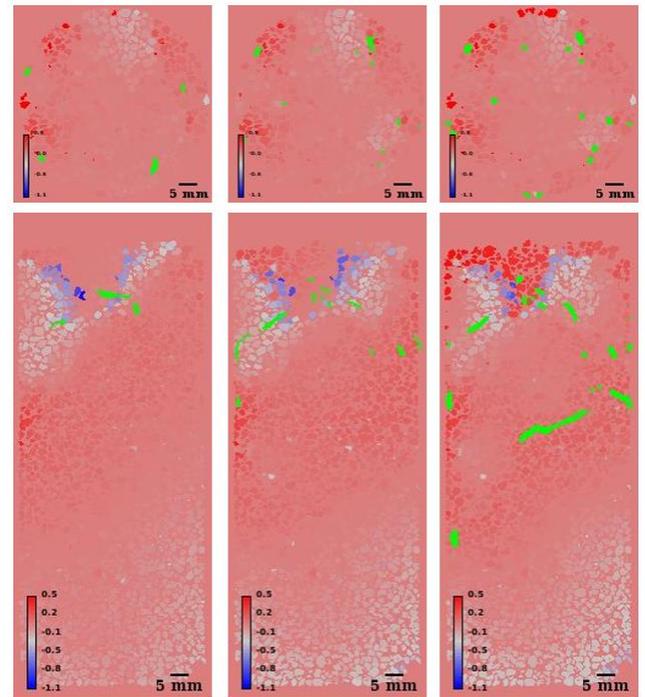
Fig.5. Discrete displacement field with root shown in green color. First row: Horizontal slices regarding the displacements along the Y axis. Second row: Vertical slices regarding the displacements along the Z axis. Displacements maps are shown between day 0 and 2 (left), day 0 and 4 (middle), and between day 0 and 6 (right). Day 0 corresponds to the day when the germinated seed was inserted. The units of the colour bar are in mm.
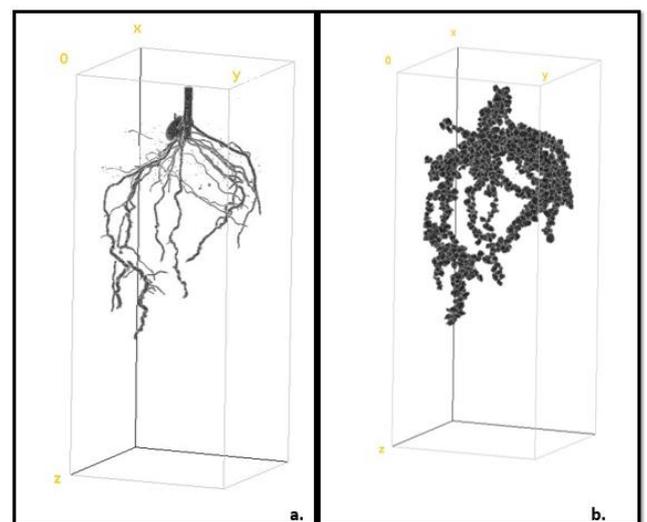
Fig.6. Identification of the grains surrounding the root system. **a.** RSA of the maize on the last day of observation; **b.** Grains surrounding that root system
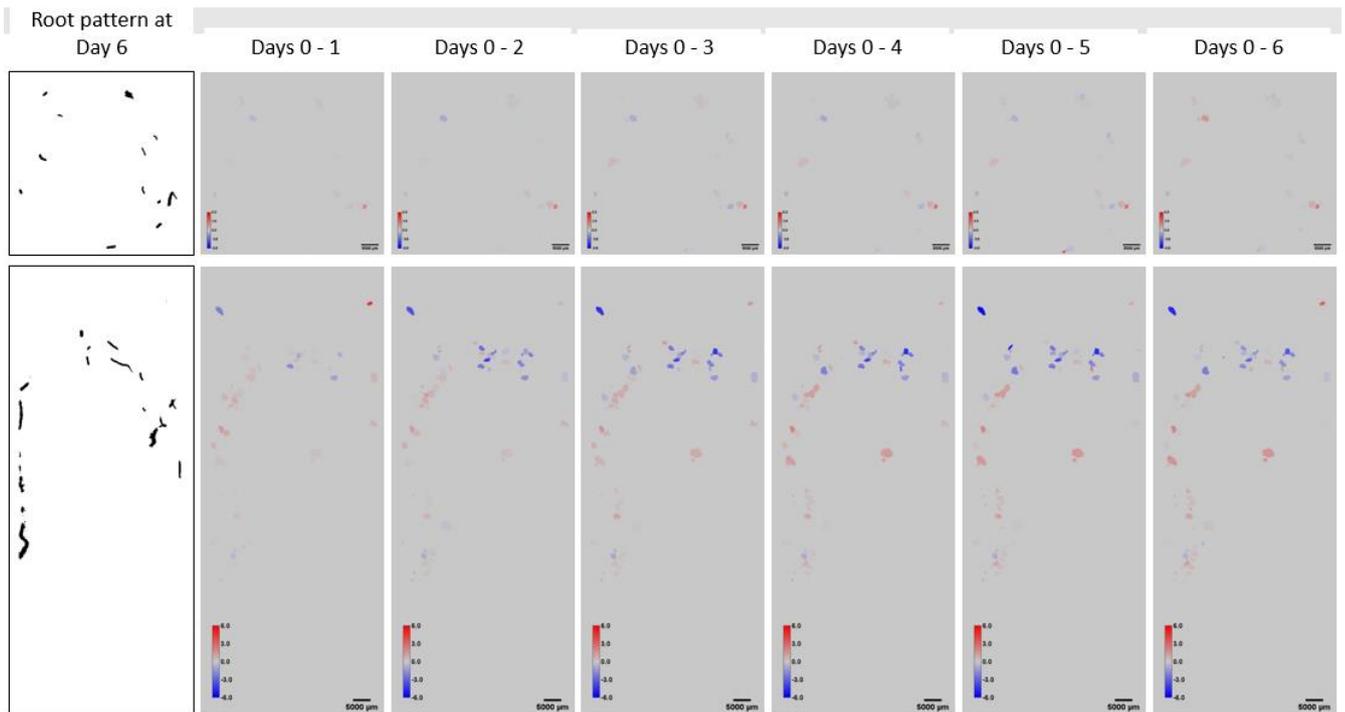
Fig.7. Identification of the root and displacement of the grains surrounding the roots. The first row represents the horizontal displacement along the Y axis, the second row, instead, the vertical displacement along the Z axis. The negative values indicate that root is pushing the grains upwards (for vertical 'z' displacements) and to the left (for horizontal 'y' displacements). The first images on the left in the first and second rows, represent the amount of root presents in these specific vertical and horizontal sections at day 6.

Fig.7 shows the evolution of the displacement fields. Such displacements are calculated in reference to the position of the sand grains at day 0. Note that the values shown are in pixels. In line with the resolution of the scans after 2 x 2 x 2 downscaling, here 1 pixel corresponds to 80 microns. The highest vertical displacement detected in the vicinity of the root is 1.44 mm– almost one grain size of displacement. The largest horizontal displacement, reached on the last day of observation, amounts to 2.39 mm. This last displacement value is about the dimension of 1.5 grains.

According to the orientation of the axes, when a displacement value is negative, it means that the particle is pushed upward and vice versa. Note that even if the root is initially present in the top part of the sample, grains located at the bottom of the sample are influenced by the root growth. In addition, when the root is pushing down, and absorbing the water, that it is at the base of the pipe, the grains are pulled up in some cases.

5. Conclusion

In this paper we analysed x-ray tomography scanned images of a specimen made of Hostun sand HN1.5-2 with a D_{50}= 1.5 mm and a maize root system.

The plant is growing healthily, following the typical scheme of the maize complex architecture reported in the literature, in the correct time frame.

During the experiment, it was decided not to introduce additional water in the specimen, to preserve the sand grains structure.

Using segmentation techniques grains, roots, water and air voxels can be classified. Individual grains are numbered and those in contact with the root can be enumerated with ease. Sand grain displacements are observed since the very beginning. These displacements may be correlated both to the evolution of the seedling and the water uptake, resulting in a change of the distribution of the pore water in the sand sample.

Further investigations are needed to distinguish, in detail, the influence of each phenomenon (root development and change in local water content). According to the displacement maps obtained, the grains are mainly moving downward, thus in the same main direction as the elongation of the root. In particular, the roots are able to displace the grains over a length of about 2.4 mm, which is almost the size of two sand particles. Once the root tip is passed, the grains do not have apparently any further significant displacements.

Further kinematic measurements will be performed to understand the length of the root tip that it is actually influencing the soil, and to understand the type of strain field produced in the soil for predicting any failure mechanisms upon root growth.

The same analysis is ongoing with a finer sand. Indeed, one of the perspectives of this work is to investigate the

influence of the grain distribution on the way the root growth influences sand microstructure, among others the local porosity [12].

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