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Improving finite element models of roots-soil mechanical interactions

Ming Yang[1], **Pauline Défossez**[1] and **Thierry Fourcaud**[2]
[1]*INRA – UR1263 EPHYSE, 33883, Villenave d'Ornon, France,* [2]*CIRAD – UMR AMAP, Montpellier, France*
**correspondence:* thierry.fourcaud@cirad.fr

Highlights: Two finite element modelling approaches have been applied and compared to simulate direct shear tests of soils reinforced by roots. The "frictional behaviour" method used with solid elements predicted shear strength of the root-soil system 4.6-6.9% higher than that predicted with "embedded beam elements". This difference can be considered as negligible. Embedded beam elements were thus chosen to discretize digitized Maritime pine root systems in a tree anchorage model. Results exhibited contrasted mechanical responses when considering different root material properties.

Keywords: Tree anchorage, root architecture, simulation, biomechanics, overturning, failure, Abaqus

INTRODUCTION

The periodic wind storms recorded during the last decades in Europe have damaged several trees, sometimes killing people in urban areas. Moreover they were responsible of significant economic loss in the forest industry, also impacting the functioning of forest ecosystems. Tree overturning has been reported as a major mode of tree damage. Minimizing the risk of tree uprooting necessitates better understanding the mechanical interactions between roots and soil. Many studies were thus carried out on tree anchorage in the past, most of them using experimental approaches consisting in pulling trees to obtain force-displacement response curves (Cucchi et al. 2004; Abd Ghani et al. 2009; Mickovski and Ennos 2003). In addition, theoretical approaches based on numerical simulations were proposed in order to investigate in more detail the effect of root architecture on tree anchorage (Dupuy et al. 2005; Dupuy et al. 2007; Fourcaud et al. 2008), as well as the effect of individual roots on soil shear strength (Mickovski et al. 2011). However, the numerical models developed still need to be improved and validated with experimental data. In particular more attention must be paid to: 1- the modelling of root-soil interface; 2- the effect of successive root failures; 3- the realism of soil properties, e.g. considering soil heterogeneities and the effect of pore water pressure.

When complex root systems with several ramifications are considered, the first point above can result in extensive computation costs and give rise to convergence problems that constitute a severe limitation for the simulations. As an alternative to the use of solid elements to model the root phase, earlier simulations were performed with structural beam elements embedded in the soil matrix (Dupuy et al. 2005). The main weakness of such a simplification is that roots and soil are connected with rigid conditions, i.e. roots cannot slip within the soil. Another limitation of these previous models comes from the fact that successive root failures were not taken into consideration (as mentioned in point 2 above), thus neglecting an important component of root anchorage. The aim of this paper is: 1- to get an estimate of the discrepancy in the simulated mechanical response between models using embedded beams and solid elements with explicit surface-to-surface interaction respectively; 2- to incorporate a model of root failure in the simulations. The initial step 1 was carried out on a typical direct shear test of a soil reinforced with individual root elements, as experimental data were available. The second step was performed on a tree overturning model considering real digitized root systems of adult Maritime pine trees (*Pinus pinaster* Ait.) and varying root mechanical properties.

MODEL DESCRIPTION

First of all, a finite element model was constructed to simulate direct shear tests of reinforced soils previously carried out by Vanel (2011). The experimental system was composed of a block of soil of dimensions 50cmx50cmx32cm (Length x Width x Depth) containing 12 identical electric wires (mimicking roots) of length 24cm standing vertically in a plane perpendicular to the horizontal shear direction. The distance between two neighbouring wires was 4cm. A given pressure was applied at the top surface of the system prior to the shear test, putting bricks at the top surface of the soil. The soil was then sheared displacing the top half of the soil block with a constant (low) velocity. Resultant forces were measured during the displacement and the resulting force-displacement curves were analysed (Figure 1).

The above system was designed using the Abaqus Finite-Element package (http://www.3ds.com/products/simulia/portfolio/abaqus/overview/). The soil was modelled as an elasto-plastic material with the isotropic linear elastic part and the plastic part satisfying the Mohr-Coulomb criteria. Roots were considered to be isotropic linear elastic. The bottom part of the soil block was encastred, i.e. no displacement was allowed during the test. The top steel frame that constituted the shear box was modelled by a rigid plate. A reference point was associated to this frame, located at its centre, where the boundary conditions were imposed during the shear process. Two options were used to model the wires (roots). In the first option, roots were meshed with solid elements that were allowed slipping within the soil matrix. In the second option, structural beam elements embedded in the soil, i.e. with no possibility of slippage of roots within the soil matrix, were used.

Simulations were composed of two static calculation steps corresponding to the two stages mentioned above. In the first step, a given pressure force was applied at the top surface of the system, in addition to gravity, and the resulting soil pre-stress field was calculated. The second step corresponded to the shear test itself and was carried out displacing the reference point of the top frame up to 0.8-1.0cm. Corresponding resultant forces were computed during this last step. The resulting force-displacement curves were used to compare the two modelling options mentioned above.

In the first modelling option, root slippage was taken into consideration through a frictional law that consists in linking the transmitted shear force to the normal force across the surfaces in contact by using the Coulomb friction model. There was only one material (of soil or root) defined at each material point. Root parts were discretized with 8-node linear reduced-integration elements (C3D8R) and the soil part was discretized with 4-node linear tetrahedron elements (C3D4). The element names a referred from the Abaqus elements library. While in the second modelling option, the root parts (wires) were discretized with 2-node linear Timoshenko beam elements (B31) embedded in the soil.

For both methods, the plate was discretized with 4-node bilinear rigid quadrilateral elements.

The model of tree anchorage was composed of a digitized root system of a Maritime pine coming from measurements conducted by Danjon et al. (unpublished data) in the Nézer Forest, a soil block and a rigid stem where a horizontal displacement of 1.34 m is applied at the top. The discretization of roots and soil was the same as in the option “embedded element” mentioned above. The elastic-failure behaviour of roots was derived from the damage model of Fibre Metal Laminates developed by Linde et al. (2004). Two different datasets of root mechanical properties were considered for the simulations presented in this paper, one in the range of values found in the literature (Dupouy, 1992), and one corresponding to softer roots.

RESULTS AND DISCUSSION

Plastic strains at the end of shear test simulations are shown in Fig. 1 in the case of “embedded elements” and “frictional behaviour” respectively. In both cases, plastic strains began to accumulate in a narrow horizontal zone which appeared in the middle plane of the soil block, which is in accordance to the observation of real shear tests. However, the first case demonstrates an oblique shear region in the back of the displaced soil block.

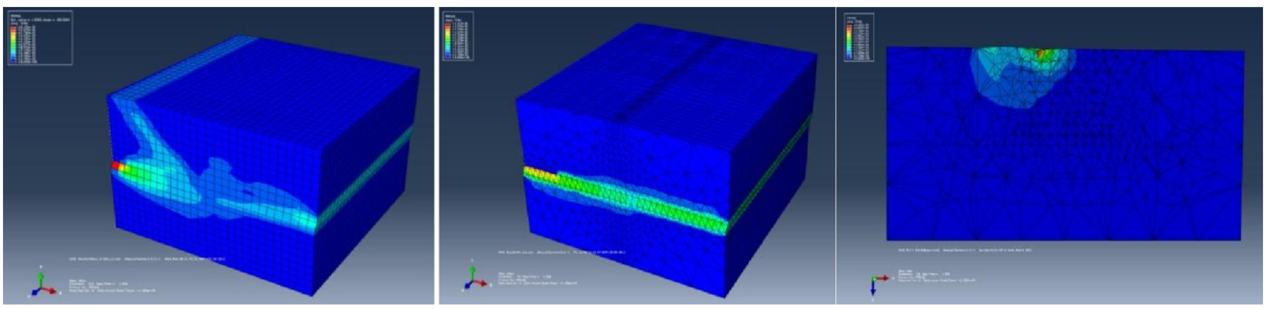

Fig 1. Distribution of equivalent plastic strain during a simulation of reinforced soil shear test using embedded beam elements (a), solid elements with frictional behaviour (b). Plastic strains during a tree overturning (c).

Results showed that both methods gave similar mechanical responses, with an increase in the reaction force in the elastic region, followed with a quick flattening of the curves that reach a maximum value which corresponded to the shear strength of the root-soil system. The recovery of the residual part after the decrease in shear stress can be explained by the reinforcing effect provided by roots. Shear strength increased with an increase in root-soil friction coefficient. Physically, this accounted for the fact that the rougher root-soil interface is, the more difficult it becomes to push the upper soil layer to move.

The model with embedded beam elements always underestimated shear strength compared with roots meshed with solid elements with frictional behaviour, but the difference does not exceed 4.6-6.9%. This result justifies using embedded beam elements in further studies of tree anchorage, as this method is much simpler to implement and the corresponding simulations are less time consuming. Simulations of tree overturning were thus performed using embedded beam elements.

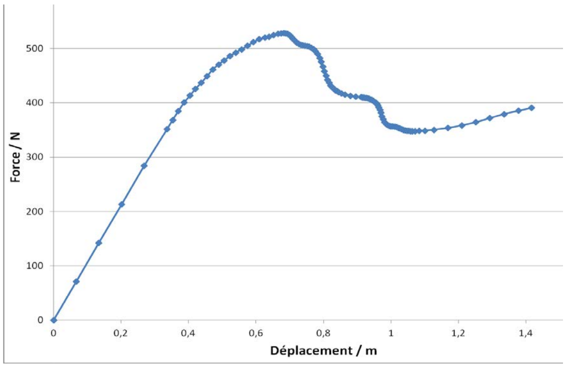

Fig. 2. Root anchorage response curve with the following root properties: Young's modulus: 20-40MPa; tensile strength: 1.35MPa; compressive strength: 0.9MPa

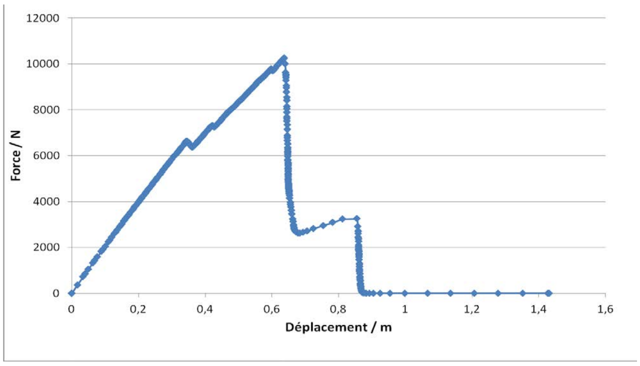

Fig. 3. Root anchorage response curve with *Pinus pinaster* root properties taken from Dupouy (1992): Young's modulus: 1-1.2GPa; tensile strength: 40MPa; compressive strength: 35MPa

The effect of successive root breakage can be observed on the response curves (Fig. 2&3). In Fig.2 the curve exhibit a peak value followed by a smooth decrease up to third of the critical force, followed by a new increase of the curve (hardening). In contrast, *Pinus pinaster* root properties (Fig. 3) induced an abrupt change of the reaction force that falls to zero at the end, which suggested a complete breakage of the system.

The present model based on previous studies (Dupuy et al., 2007) has incorporated the modelling of successive root breakage to give a more realistic modelling of tree anchorage. It could be applied to different tree species with different environmental conditions (soil conditions; roots damaged by parasites) by introducing appropriate values of the corresponding mechanical parameters. In our study this model aims to better understand the anchorage of *Pinus pinaster* and to extract key influential factors. Validation of the model will be carried out in a subsequent study, using experimental data.

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