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MODELLING THE INFLUENCE OF MORPHOLOGICAL AND MECHANICAL PROPERTIES ON THE ANCHORAGE OF ROOT SYSTEMS

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Abstract

A sensitivity analysis based on numerical simulation is presented, in order to investigate the anchorage resistance of root systems. The form and mechanical characteristics of roots used in the models were derived from experimental results found by previous authors. Finite element models were developed to analyse the mechanical process of uprooting. The analysis of local phenomena occurring during uprooting was performed using 2D models, whereas the anchorage of complete tree root systems used 3D models. The principal parameters which determined root shape and material properties were varied so that their influence could be evaluated. The design of experiments method (DOE) was used to generate an optimal number of root / soil configurations. It was possible to determine the influence of each of these parameters, therefore the modelling carried out provided a broad overview of the interacting mechanisms taking place during uprooting.

Introduction

The understanding of soil/root mechanical behaviour concerns various research areas, including that of slope stability, soil reinforcement or windthrow. However the knowledge concerning tree underground mechanics remains largely incomplete due to: 1), a lack of suitable measuring tools in experimental studies investigating underground mechanisms occurring during overturning or plant pull-out, 2), *in situ* experiments must face the huge diversity of morphological and physical properties of root systems and soil properties, which render difficult explanations of tree instability factors.

In recent year, few models has been developed which incorporate root system shape and soil characteristics (Ennos 1989, Mattheck et al 1997, Niklas et al. 2002). The development of realistic mechanistic models of tree anchorage would be very useful to explore the influence of architectural diversity of root systems and soil properties on tree anchorage, and would also complement the difficult and time consuming experiments. Such models would provide also a better understanding of internal physical processes involved during mechanical loading.

The objective of the study presented in this paper was to use the finite element method to quantify the respective influence of the geometrical and mechanical properties of roots and soil on the resistance of the anchorage. This problem was expressed in terms of a wide parametric study, whereby numerical techniques appeared to be suitable to solve such a complex and multi factorial problem.

Materials and methods

The overall resistance of a complete root system results from the contribution of a large number of roots with different sizes and orientations. Therefore, an analysis of this phenomenon is necessary at two different scales, in order to provide the widest and most fundamental understanding of the mechanisms involved. The local aspect of the analysis concerned simulations of simple branched structures submitted to pulling forces, and focused on elementary mechanisms, e.g. sliding at the root/soil interface, breaking of the root or shearing in the soil.

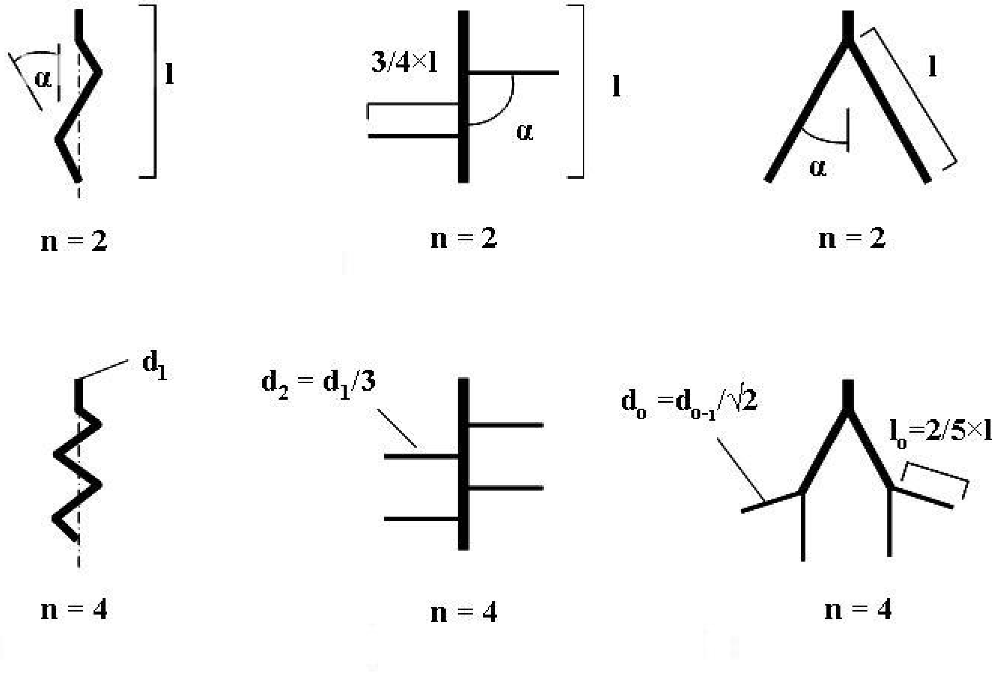

Fig. 1: For the 2D analysis, the elementary branching patterns used for the sensitivity analysis were parameterised in order to vary the shapes, where: α = angle from initial axis, d = diameter, l = length, n = number of external links, or bends in zig-zag. The elements of the first column represent group 1, the second column group 2 and the last column group 3.

Simulations of uprooting individual roots were carried out initially. These models were made up of simple branching patterns buried in soil (Figure 1). The shapes were derived from the three possible types of branching event occurring on an axis: no branching, lateral branching (herringbone like systems) and terminal branching (dichotomous systems) as described by Fitter 1987. Numerical parameters defined and controlled the shapes, e.g. branching angle, number of branching events or axis length. The scale of the root elements was also a varying parameter. For a given scale, all root elements had the same volume in order to focus only on the effect of form. The mechanical behaviour of wood, soil and interface was modelled using classical models. Roots were assumed to be an elastic perfectly plastic isotropic material, with Von Mises yield criterion. The soil behaviour was modelled using the Mohr Coulomb shear criterion. As the analysis was performed at a local level, the action of the soil on root elements was characterised by a uniform stress state "*p*". In order to simulate the friction between the soil and the roots, a simplified perfectly plastic Coulomb model was used.

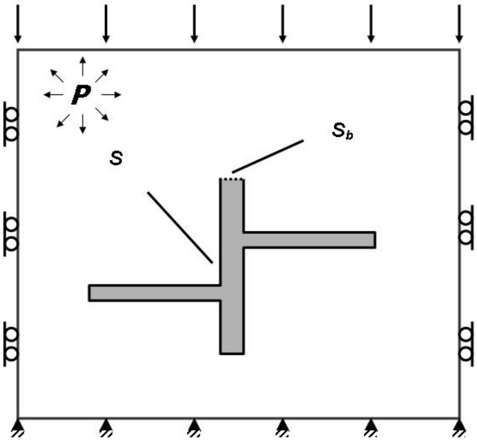

Fig. 2: Boundary conditions imposed at the borders of the model root-soil system, which allowed the application of a constant pressure around the root element.

Parameters	Group 1	Group 2	Group 3
l/s	1 - 1.5	1 - 1.5	1 - 1.5
n	2 - 4	2 - 4	2 - 4
α (°)	10 - 20	30 - 90	15 - 60
c (kPa)	1 - 4	1 - 4	1 - 4
f	0.1 – 0.5	0.1 – 0.5	0.1 – 0.5
p (kPa)	1 - 3	1 - 3	1 - 3
s (m)	1/8 - 1/5	1/8 - 1/5	1/8 - 1/5

Table 1: Input parameters of the models, and their array of variation for each of the three groups of root systems.

Boundary conditions were applied to the studied domain in order to reproduce the action of the surrounding infinite earth. Translation on lateral faces was fixed tangentially, and the underside face was blocked. The analysis were performed by applying upward displacement increments to the root basal surface "*Sb*" (Figure 2). Table 1 summarize the parameters being studied during the analysis. Root geometry was simple enough to build a realistic mechanical model involving the three main components of the failure: soil failure, root breakage and sliding of the contact surface between soil and roots. The model was implemented using plane strain elements. The resistance of a root element was determined as the maximum reaction force recorded during the longitudinal displacement. The resulting forces were transformed into an addimentionnal value to generalize the results to the range of scales analyzed. Thereafter, the design of experiment method (D.O.E) was used to generate an optimal number of root/soil configurations in order to quantify the influence of each parameter individually (Dupuy et al 2003).

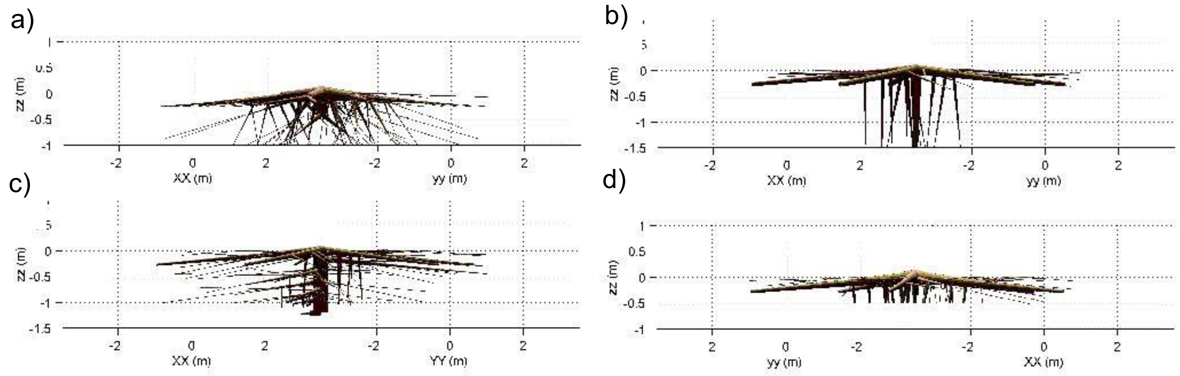

Fig. 3: Four types of root systems denoting highly opposed rooting strategies were selected for the simulations: a) heart root system with variable branching angle, b) tap root system with large sinker of 1.5 m deep and lateral roots, c) herringbone system with one major tap root and second order roots and d) plate system with large lateral roots and smaller sinker roots. Horizontal and vertical axes refer to width and depth (m) respectively.

A global analysis was also carried out on models of complete root systems and dealt with topological and structural effects. In a complete root system (Figure 3), a large number of combinations of the basic branching patterns described in figure 1 exist, leading to the architectural complexity observed in nature. Therefore, it was difficult to parameterize such complex structures, hence this study focused on four root systems which represented a variety of architectural characteristics. For this purpose, a simulation tool has been developed (SIMUL 3R, developed by L. Dupuy under Matlab ©, Mathworks), based on a local probabilistic definition of branching, conditioned by state variables. The resulting architectural data were recorder in MTG files (Godin and Caraglio 1998). Additional programs have been developed to mesh automatically roots and soil from MTG files for both 2D and 3D architectures. The four root systems included heart-, tap-, herringbone and plate-like root systems (Figure 3a, Kostler et al 1968). The heart system, typical of Douglas fir and red oak, was characterized by the appearance of forks at a distance of 1 m from the stem (Lyford 1980). The distance between lateral roots was set to 20 cm and rooting depth was 1 m (Lyford 1980). The tap root system (Figure 3 b), e.g. *Pinus pinaster* and *Pinus sylvestris*, possessed no forks, and the distance between roots was set to 30 cm (Coutts 1987). The rooting direction was either vertical or horizontal, as found in most coniferous trees (Laitakari 1927, Puhe 2003), and the depth reached a maximum of 1.5 m. The tap root had the same basal diameter as the first order laterals. The third root system studied was a herringbone like root system (figure 3 c), and possessed uniformly distributed, generally horizontal, second order lateral roots along the length of the main tap root. The final root system type was representative of plate root systems (figure 3 d) e.g. *Picea sitchensis,* where depth was limited to 50 cm. Although there was no first order tap root, branching characteristics were similar to the tap root system.

The anchorage of these simulated root systems has been analysed in 4 different soils (dry sand, wet sand, soft clay and strong clay). All the root systems were modelled using 3D beam elements. The soil elements were modelled using 20 node brick elements and the same boundary conditions as in figure 1 were imposed on the lateral- undersides of the soil-root system. The root system nodes were fixed rigidly to the closest soil nodes in order to model the root soil interaction. Each root system was attached to a stem-like structure, and wind loading was simulated by applying a force at a height of 5m up the stem.

Results and discussion

The failure of a single root element is a consequence of the combined effect of failure in the root, soil shearing and sliding at the root-soil interface. The type of failure and uprooting resistance depends on the root-soil configuration e.g. in non-branching structures, failure occurs in the soil and at the root-soil interface as well as by shearing in the soil. However, when lateral roots are present, failure generally occurs first in these roots during uprooting. Table 2 summarizes the influence of each parameter. It was found that "*l*" had the most significant effect on the resistance of the root element. Indeed, as a result of a constant volume, the increase in the axis length led to a decrease in diameter, which decreased both the bending resistance of lateral axis and the thickness of displaced soil. "*n*" was the second most significant parameter, notably for branching structures. It results from a change in proportion of biomass allocated from vertical to lateral axis. It also created a wider block of soil being displaced during the pulling. The cohesion of the soil was particularly important for the group 1, because the diameter was important due to the constant volume. Consequently, the failure happened mainly in the soil, which determined most of the element resistance. (Dupuy et al 2003). The resistance of an element of constant material properties, disregarding the group, was well predicted by the basal diameter and the number of internal connections in the element.

Coefficient Parameter	Root system type		
	Group 1	Group 2	Group 3
Cte	0.46	0.52	1.20
l	-0.05	-0.82	-1.70
n	0.10	0.61	0.84
α	0.20	0.09	-0.13
c	0.22	0.20	0.18
f	0.06	0.24	0.13
p	0.10	0.01	0.02

Table 2: Influence of specific parameters affecting root tensile resistance. Numeric values represent the percentage increase of the resistance produced by the increase of 1% of the corresponding factor.

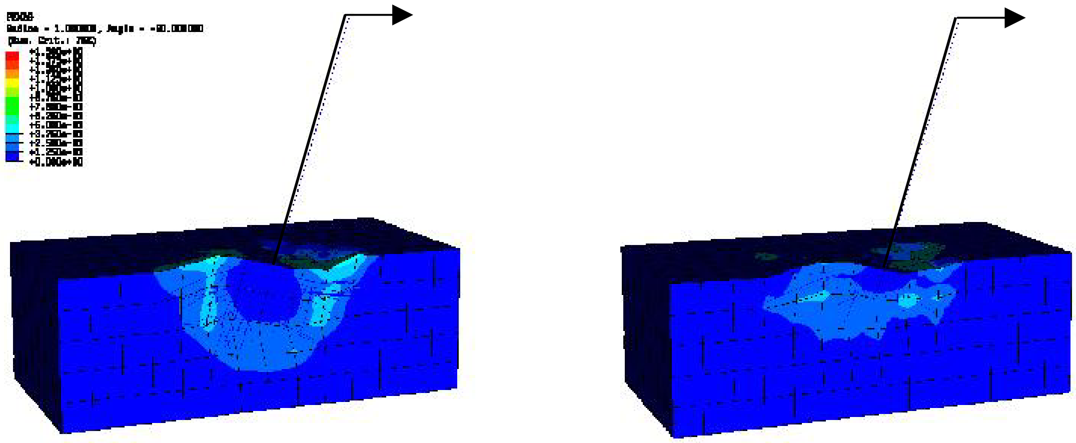

Figure 4: Field of equivalent plastic strain in the soil cross section for a) herringbone and b) plate root systems in dry sand. Despite the apparent disparities in failure modes, the differences of resistance to bending are rather similar.

When simulations of lateral bending of stems plus entire root systems were carried out, it was found that the differences in topology and architecture led to large changes in the type of failure and in the overall resistance to bending (Figure 4). The heart root system was found to be the most resistant to overturning on clay soils, but on sandy soils, the deep tap rooted system was better anchored. The herringbone root system was only slightly more resistant than the plate root system, and in strong clay less resistant. The tap root system was clearly very sensitive to changes in soil conditions, whereas the other systems appeared to be less affected by different soil conditions.

From these initial simulations it can be concluded that the resistance to bending of the root system was strongly related to soil type. Also, It appeared clearly that root morphology interacted with the mechanism. The depth seemed to be the most important factor, and particularly for sandy soils. Mickovski 2002, showed that the resistance of laterally loaded piles in sand was proportional to the third power of depth in the soil, but was related to depth squared for clay-like soils. With regards to the herringbone system, it is not surprising to find that it was not particularly resistant to overturning in sandy soils, as the principal tap root axis was only 1 m deep. However, the heart root system, characterised by a large number of vertical, horizontal and oblique roots, was the most resistant in clay soils, as also found in experimental studies (Stokes et al 1999). This higher resistance could be explained by a greater number of small roots, which resist tension better than if only a few large ones were present. However, the overall resistance of each root system results in different sets of parameters, and it is not possible to associate a particular characteristic of anchorage to specific parameters. These hypotheses need to be quantified with further investigations, by e.g. a similar study carried out on simple 2D root elements.

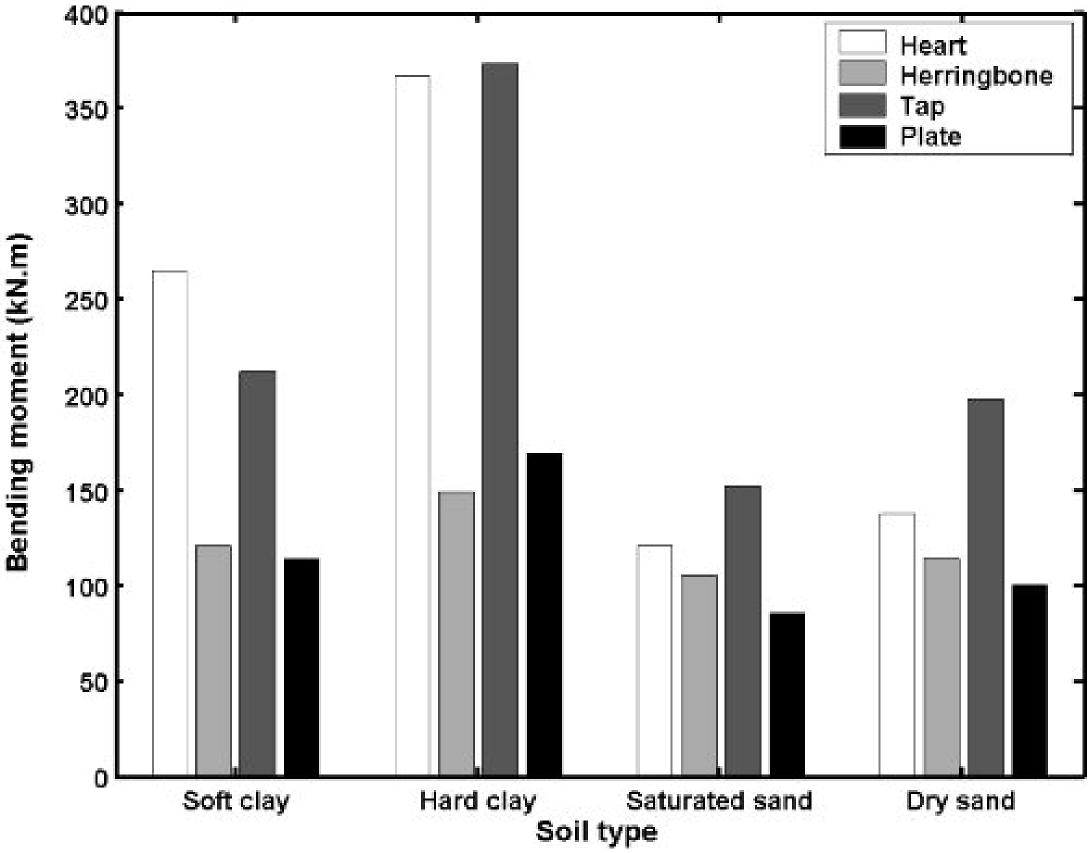

Figure 4: Maximum bending moment of four different root systems in four different soils. Deep rooting tap systems are the most resistant to uprooting in sandy soil, whereas heart root systems are the most resistant in clay soil.

Conclusion

Numerical methods were used for the mechanical analysis of root anchorage. These methods provided a broad overview of the physical phenomena involved during the process of uprooting. However, the models developed in this study present important simplifications, and are in many ways idealistic. The use of 2D modelling prevents many physical processes being described e.g. the flow of soil in a third direction or 3D root structures. When using 3D models, the intricate interactions between soil and root elements cannot be analysed due to the complexity of the structures involved. Root material properties also remained constant along the length of each axis, whereas in reality, anatomical changes in root wood can result in huge differences in tensile and bending strength along a root (Stokes & Mattheck 1996, O'Loughlin & Watson 1979). However, the models presented could clearly show the effect of changes in root morphologies. In addition, the main physical phenomena explaining anchorage failure e.g. soil plasticity, shearing at the soil-root interface, or failure in the root, were all taken into account. It must also be underlined that the type of analysis developed in this study i.e. coupling local and global analyses, could be used to provide a simplified method for the estimation of root anchorage.

Acknowledgements

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