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Tree stability to wind : modelling tree anchorage and analysing key contributing factors

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Résumé :

Cette étude vise à mieux comprendre le processus de déracinement de l'arbre et à identifier les traits structuraux et matériels (racines, sol) ayant un effet du premier ordre sur l'ancrage racinaire dans le cas du Pinus pinaster. Un modèle d'éléments finis a été développé et permis de simuler et suivre la chronologie des ruptures successives au cours du déracinement. Un seuil de rupture globale de l'ancrage est ainsi défini comme une résultante de l'architecture et de la résistance des matériaux en jeu (racines, sol). Dans la même logique, nous nous sommes appuyés sur les données expérimentales pour construire une architecture simplifiée du système racinaire du P. pinaster. L'importance des différentes composantes sur le mécanisme d'ancrage a été étudiée et le rôle essentiel joué par le pivot et les racines traçantes montré.

Abstract :

This study aims to better understand the tree uprooting process and to identify both root structural features and material properties which have first-order effects on tree anchorage strength for Pinus pinaster. A Finite Element Model has been developed and allowed for simulating and tracking sequential root failure during the course of tree overturning. An overall tree anchorage strength is thus defined as the resultant of contribution of root system architecture and material strength (roots, soil). In the same spirit, we have relied on root architectural data to build a simplified root system pattern with P. pinaster features. Importance of different root components has been studied and the essential role of the taproot and shallow roots demonstrated.

Mots clefs : damage mechanics, root failure, tree anchorage, root system architecture, sensitivity analysis

1 Introduction

Windstorms are the major hazard affecting European forests and causing timber losses [1]. Uprooting is reported as the major failure mode during windstorms. However the mechanism is largely unknown.

This paper investigates the uprooting process as well as involved contributing factors through a mechanistic approach. Tree underground overturning behaviour was modelled with the Finite Element Method. Effects of root architectural traits and material properties of soil and roots were evaluated through systematic sensitivity analysis. Different factors involved in the tree overturning process have been classified with respect to their impacts on tree anchorage strength.

2 Model description

The anchorage model was developed using the finite element method within Abaqus 6.13 [2]. Modelled wind-induced underground overturning process results from root system architecture (RSA), material properties of roots and soil, and root-soil mechanical interactions (Figure 1). Wind action on the tree is modelled by a horizontal displacement (1.2 m) applied on the top of a rigid stem (1.6 m in length). The stem is attached to the top of the root system in the soil (10 m in length, 10 m in width and 5 m in depth ; meshed into 3D solid brick elements with reduced integration). At the centre of the soil block corresponding to the root system location, a parallelepiped area (6 m in length, 6 m in width and 1.25 m in depth) is partitioned for refined mesh. The mechanical behaviour of root material is presented in Section 2.1. Soil material is defined to be homogeneous, linearly elastic and plastic with Mohr-Coulomb criterion. To introduce realistic material properties with least additional model complexity, the model was parameterised by a minimum of mass, stiffness and strength characteristics for roots and soil. Table 1 shows the associated parameters obtained from measurements either performed during the corresponding tree-pulling experiment (soil) [2] or published previously for similar greenwood materials (roots). RSA is explicitly described in the model and meshed into 3D Timoshenko beam elements (see Section 2.2). Model outputs include the response curve of turning moment (TM) as a function of deflection angle calculated at the stem base, the anchorage strength characterised by the maximum turning moment (TM_c), distributions of specified variables (stress and strain components, the damage variable, etc.) within the root system and soil medium.

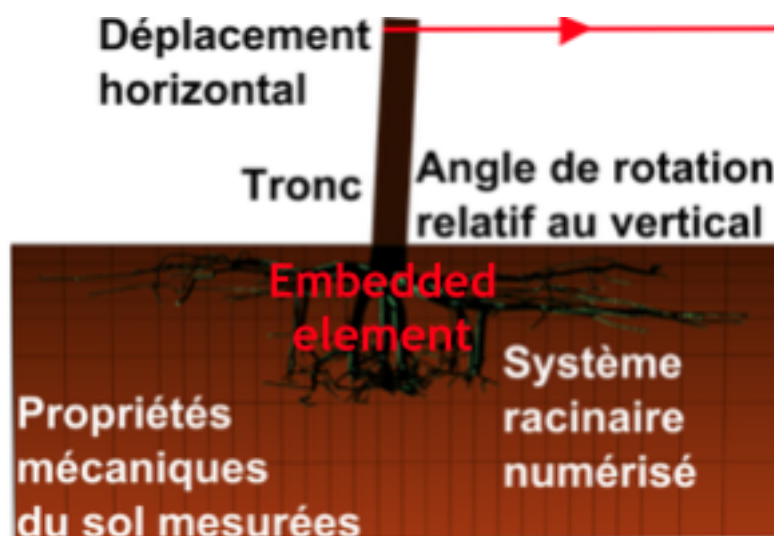


FIGURE 1 – Anchorage model with root system architecture and material properties measured for tree-pulling simulations.

Item (soil)	Value	Units	Item (roots)	Value	Units
Density	1410	$kg\ m^{-3}$	Density	421.4	$kg\ m^{-3}$
Modulus of elasticity	19.86	MPa	Modulus of elasticity	8	GPa
Poisson ratio	0.33	-	Shear modulus/Young's modulus	0.0755	-
Cohesion	21.402	kPa	Tensile strength	43.2	MPa
Friction angle	14.62	$^\circ$	Compressive strength	20.6	MPa
Dilation angle	0	$^\circ$	Energy of fracture	209.4	$J.m^{-2}$
			Viscous parameter	0.000075	-

TABLE 1 – Mechanical properties of roots and soil material : elastic and plastic (Mohr-Coulomb) for soil and elastic-brittle for roots

2.1 Constitutive law for root failure

We adapted the constitutive law proposed by Linde et al. (2004) to describe root failure in tension and compression, thus in bending [3]. Roots are assumed to be a quasi-brittle material characterised by elastic-failure behaviour. Based on continuum mechanics, the stress-strain relationship characterising the initial elastic state at a material point of the root is determined by

$$\boldsymbol{\sigma} = \mathbf{C} : \boldsymbol{\varepsilon}, \quad (1)$$

where the elastic tensor \mathbf{C} defines the constitutive relation between the stress tensor $\boldsymbol{\sigma}$ and the strain tensor $\boldsymbol{\varepsilon}$.

2.1.1 Damage initiation criterion

The damage state at a material point is marked by reaching the scalar criterion defined by

$$f = \sqrt{\frac{\varepsilon_{11}^t}{\varepsilon_{11}^c} \varepsilon_{11}^2 + \left(\varepsilon_{11}^t - \frac{\varepsilon_{11}^t{}^2}{\varepsilon_{11}^c}\right) \varepsilon_{11}} > \varepsilon_{11}^t, \quad (2)$$

where ε_{11} is the axial strain component and

$$\varepsilon_{11}^t = \frac{\sigma_{11}^t}{E}, \quad (3a)$$

$$\varepsilon_{11}^c = \frac{\sigma_{11}^c}{E}. \quad (3b)$$

σ_{11}^t and σ_{11}^c are respectively tensile strength and compressive strength of the root material and E is the Young's modulus.

2.1.2 Damage evolution rule

If the damage initiation criterion is reached, the scalar damage variable d is defined as the damage evolution rule by

$$d = 1 - \frac{\varepsilon_{11}^t}{f} \exp\left(\frac{-E\varepsilon_{11}^t(f - \varepsilon_{11}^t)L^c}{G_f}\right), \quad (4)$$

where L^c is the characteristic length of the specified element, and G_f the fracture energy. d characterises the degraded stiffness \mathbf{C}_d at the material point defined by

$$\mathbf{C}_d = (1 - d) \cdot \mathbf{C}, \quad (5)$$

and the degraded stress tensor is computed through

$$\boldsymbol{\sigma} = \mathbf{C}_d : \boldsymbol{\varepsilon}. \quad (6)$$

To obtain a better numerical convergence, d is regularised by adding a viscous effect defined by

$$\dot{d}^v = \frac{1}{\eta}(d - d^v), \quad (7)$$

where η is the viscosity parameter controlling the rate at which the regularized damage variable d^v approaches d . The modification of damage variable could cause a delay in damage evolution. Therefore to minimize the eventual discrepancy, the value of η is defined to be very small compared to the characteristic load increment.

2.2 Root system architecture

In the anchorage model, a species-specified description of RSA is attempted through a 3D root pattern (CASE0) described by main root classes with realistic dimensions extracted from field measurements for *Pinus pinaster* [4]. To represent the observed large variability of RSA and evaluate impacts of main root classes on TMc, 12 morphological variations (CASE1-CASE12) are designed by separately removing for each case one main root class from CASE0 (the taproot, windward shallow roots, etc.). Figure 2 shows four examples of these variations. The impact of a root component i (missing in CASE i) $C(\text{CASE}i)$ was estimated by

$$C(\text{CASE}i) = \frac{TMc(\text{CASE}0) - TMc(\text{CASE}i)}{TMc(\text{CASE}0)}. \quad (8)$$

3 Sensitivity analysis

To extract relevant contributing factors to tree anchorage strength, geometric parameters of main root components (length, diameters ; 23 parameters) and material properties of roots and soil (11 parameters ; see Table 1) were estimated in terms of impacts on TMc. For all parameters, three levels of values were defined by a variation of $\pm 20\%$ with respect to the reference value (CASE0). The Taguchi's orthogonal arrays L54 and L27 were separately applied for the two parameter sets to reduce the large number of simulations. The number of simulations to be performed was thus reduced (from 3^{23}) to 54 for the geometrical parameter set and (from 3^{11}) to 27 for the material parameter set. The sensitivity of the system to a specific input variable (either from the geometrical set or from the material set) was defined by its influence on the output variable (TMc in our case) measured by the relative variation :

$$Var_j^i = \frac{\bar{Y}_j^i}{\bar{Y}} \quad (9)$$

where Var_j^i is the relative variation of TMc estimated for the input factor i (either geometrical or material parameters) at the level of variation j (-20%, 1 or +20%), \bar{Y} the mean value of TMc averaged over all

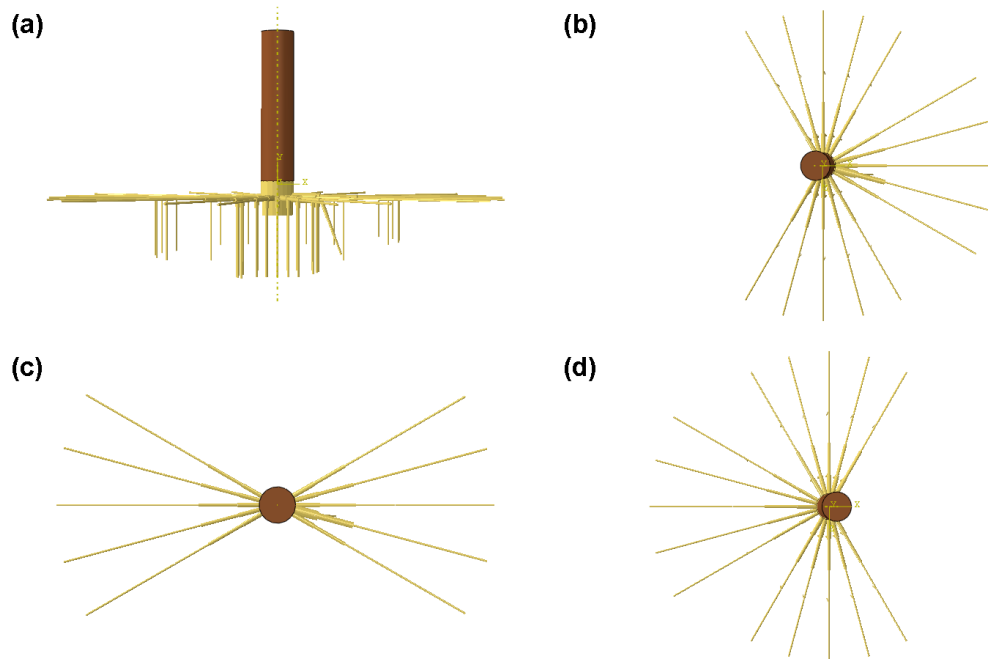


FIGURE 2 – Four examples of morphological variations for the root pattern : (a) without a taproot ; (b) without windward roots ; (c) without roots in the sectors perpendicular to the prevailing wind direction ; (d) without leeward roots.

the simulations performed for the parameter set (either geometry or material), and \bar{Y}_j^i the mean value of TMc averaged over simulations at the level of variation j for the factor i .

4 Results

4.1 Elastic-failure behaviour of a root

Tensile, compressive and bending tests were performed numerically on a cantilever beam of 1 m in length and 0.04 m in diameter considered as a root segment, with a characteristic length L_c of 0.1 m and root material properties given in Table 1. Figure 3 illustrates the quasi-brittle behaviour demonstrated by these numerical tests.

4.2 Anchorage strength and contributing factors

The TMc estimated for CASE0 is 36.2 N.m, reaching the same level of empirical TMc estimates for the same species of a similar size and 30% smaller than the midpoint of the range [5]. The simulated sequential root failure showed in Figure 4 explains two main phenomena characterising tree anchorage failure, namely the sequential stiffness reduction and the overall physical failure of the root-soil system. We propose the hierarchical impact of root components to tree anchorage as follows : taproot > windward shallow roots > perpendicular shallow roots > windward sinker roots > any other component of minor impact. RSA plays a predominant role in root anchorage over material properties of roots and soil.

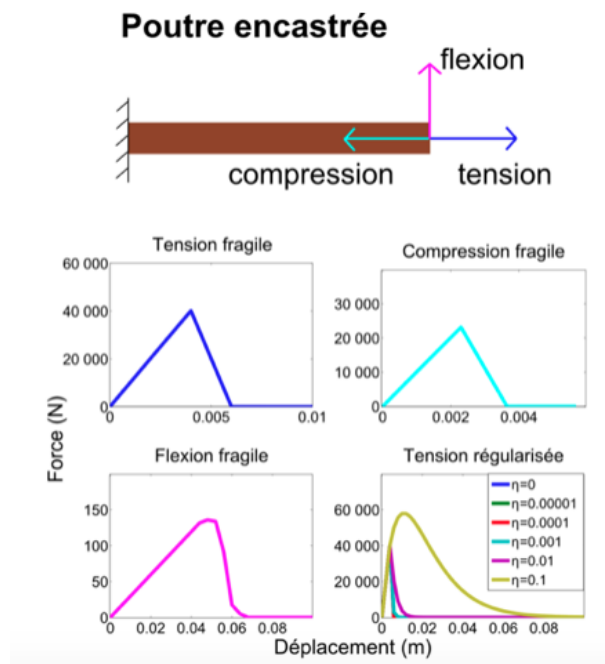


FIGURE 3 – A cantilever beam subject to tension, compression and bending, with numerical viscous effect illustrated.

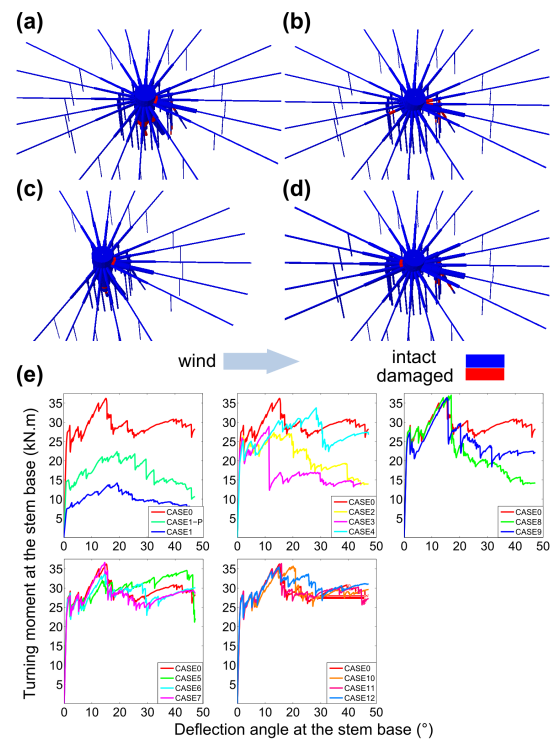


FIGURE 4 – Simulated sequential root failure for different root patterns and response curves of TM as a function of deflection angle for CASE0 and CASE1-CASE12.

5 Conclusion

The model predicts tree anchorage strength in good agreement with empirical estimation. Simulations reveal underlying connections between individual root responses and the tree overall response to overturning.

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