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A QUANTITATIVE FRAMEWORK FOR MULTI-RISK ANALYSIS OF WIND AND RAIN ON TREES

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Abstract

Green spaces are among the most vulnerable areas in urban environments as they experience different levels of damage in extreme weather conditions. The stability of natural elements such as trees, which are valuable assets in urban areas, is threatened directly or indirectly by the occurrence of natural hazards such as wind, rainfall, and drought. This paper illustrates the conceptual foundations and the initial modeling steps of a novel approach for the conduction of multi-risk analysis for urban trees from the combined action of wind and rain. Operationally, the approach relies on the engineering modeling of the mechanical response of trees to the two risk agents and on the definition of vulnerability for relevant limit states.

Keywords: trees, wind, rain, multi-risk, vulnerability, numerical modeling.

1 Introduction

The planting of vegetation and the creation of green spaces are nature-based solutions to mitigate climate change's impacts in urban areas. However, the vulnerability of urban trees during hydrometeorological, climate-induced events like strong winds, heavy rain, and drought can pose risks to people and material assets in their vicinity. The maintenance and management of these valuable urban resources can be pursued through a risk-based process involving the identification of risk factors, the phenomenological description of their interactions with vulnerable elements, the engineering definition of relevant limit states, and the estimation of the probability of attaining them. These goals can be pursued through a synergetic approach involving a multi-risk framework and the quantitative numerical modeling of tree-hazard interactions.

Vulnerability modeling is a critical module of the risk analysis process. This study synthetically illustrates the results of a probabilistic analysis aimed at establishing the vulnerability of trees towards two relevant hazards (wind and rain) which typically threaten their stability. More specifically, vulnerability is defined in terms of the attainment of two limit states: stem breakage and uprooting.

Although significant efforts have been made in addressing tree stability and root-soil interactions, as demonstrated in the works of Fourcaud et al. (2008), Lee, D. T. T., (2016), and Kim et al. (2020), further research is necessary to increase knowledge about the complex interactions between trees, root systems, and soil. Especially, the current understanding of how soil properties affect tree stability is rather limited. As such, there is a pressing need for further investigations in these areas to improve both the accuracy of models and our fundamental comprehension of tree stability under varying soil conditions.

The paper presents synthetically a novel, simplified numerical finite element model, which was created to model the tree-root-soil system and to capture salient aspects of the complex biological and mechanical phenomena occurring within it. A Monte Carlo simulation-based approach was implemented to investigate the scenario-based attainment of the two limit states accounting for the variability of geometric and mechanical parameters.

2 Numerical modeling approach

Previous quantitative studies indicate that the presence of roots can enhance the mechanical resistance of shallow soil through the contribution of an additional cohesion in the context of the Mohr-Coulomb failure criterion (Fredlund et al., 1987). Root cohesion is variable with depth, and its spatial variability results from the depth-variant distribution of roots in the soil, the patterns in root architecture, and tensile strength. Root cohesion generally diminishes with depth, but vegetation type, soil conditions, and other environmental variables affect its spatial behavior (Nguyen et al., 2019; Zhang et al., 2020). In this study, a simplified finite element model of the root-soil system was constructed with the help of PLAXIS software, to investigate the probability of failure for the uprooting limit state. The presence of roots within the soil was modeled via an equivalent composite soil exhibiting higher cohesion than the non-rooted soil. The progressive radial reduction in root cohesion with distance from the collar area was implemented. The structure of the model is shown in Figure 1, which illustrates the system's exposure to wind force (F), the resultant moment (M), and above-ground biomass (AGB). The resultant moment is a crucial factor in understanding the system's stability and is calculated by multiplying the wind force by the height of the tree (H).

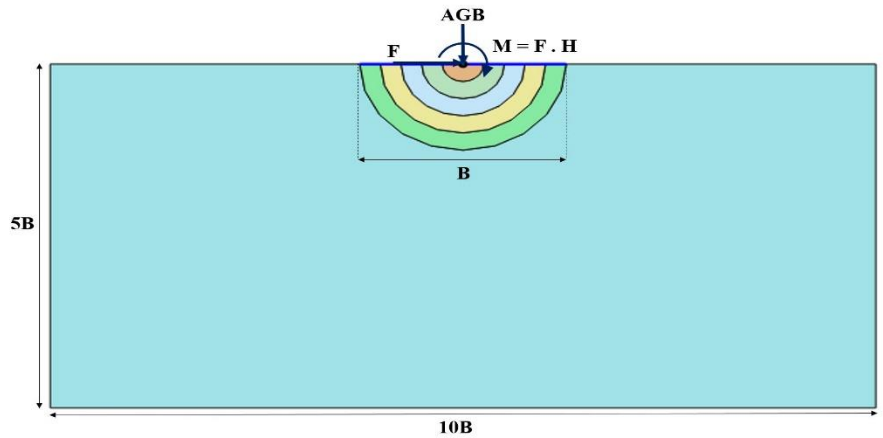

Figure 1: Numerical model for rooted soil.

3 System parameterization

Despite ongoing scientific debate about varying wind resistance among tree species, the current unavailability of direct and controlled experiments hinders the obtaining of definitive statistical evidence for inherent differences in wind susceptibility among species (Gardiner, 2021). In this research, data on various prevalent tree species in Italy were utilized to develop a numerical model that includes four geometric variables: tree height, crown height, crown width, and Diameter at Breast Height (DBH). Wind actions and the geometric and mechanical properties of trees and soils were parameterized as described in the following.

3.1 Wind action parameterization

Wind actions on trees are affected by uncertainties in parameters characterizing the wind field (mean wind velocity, turbulence intensity, dominant wind direction), and parameters characterizing the global aerodynamic properties of the tree. In this study, as a first rough approximation, only the equivalent static component of wind loading acting on trees was retained, based on Equation (1). Where V is the mean wind speed (m/s) at the canopy top, A is the estimated crown size serving as the invested wind area (m^2), C_D is the drag coefficient that has been assumed as a constant factor with respect to the mean wind speed, G is the gust factor and, ρ_{air} is the density of air (kg/m^3). An elliptical shape for the tree crown was assumed and the invested area was estimated based on the height and width of the crown.

$$\boldsymbol{F = \frac{1}{2}\rho_{air} G\, V^2 C_D A} \quad (\mathbf{1})$$

3.2 Tree parameterization

In the model, the joint probability distribution of three distinct parameters - height, DBH, and invested area - has been used, determined after adopting Gaussian distributions for each marginal distribution. In the absence of detailed data, root expansion within the soil was approximated by the nonlinear analytical relationship between trunk diameter and tree root spread provided by Day et al. (2010) with a value of R^2 = 0.89, where *y* is the maximum root radius (m), and *x* represents trunk diameter (cm):

$$\boldsymbol{y = 5.266(1 - e^{-0.096x})} \quad (\mathbf{2})$$

Furthermore, the model incorporated the effect of above-ground biomass (AGB) which was estimated based on the model by Kebede and Soromessa (2018) with the following relationship (R^2 = 0.94):

$$\boldsymbol{y = 0.623(DBH)^{1.352}\ (H)^{0.703}} \quad (\mathbf{3})$$

3.3 Soil parameterization

Gaussian distributions were adopted to describe the range of variation of the mechanical properties of a homogeneous and isotropic drained soil medium (i.e., cohesion, friction angle, and modulus of elasticity) relevant to the numerical model. Root cohesion was defined within a range of 0-100 kPa, with an assumed exponential decrease across the specified layers in accordance with Bischetti et al. (2009). Furthermore, the impact of rainfall was included in the model through alterations in the groundwater level. The range of variation in soil parameters has been shown in Table 1.

Table 1. Range of soil mechanical properties

Parameter	***Range***
Soil cohesion	1-50 (kPa)
Friction angle	10-48 (degree)
Modulus of elasticity	1-45 (MPa)

4 Definition of limit states

The numerical modelling process is aimed at replicating the behaviour of trees with respect to the attainment of the two reference limit states of uprooting and stem breakage. The stem breakage limit state is defined in terms of the comparison between the wind-induced stresses in the outer part of the stem and the maximum bending moment that a tree stem can stand without breakage ($STEM_{res}$), evaluated by the simplified relationships reported in Equation (4):

$$\boldsymbol{STEM_{res} = \frac{\pi}{32} \times MOR \times (DBH)^3} \quad (\mathbf{4})$$

where DBH is the diameter at breast height and MOR is the modulus of rupture of green wood (Morgan and Cannell, 1994). If the bending moment at the stem exceeds the $STEM_{res}$, the stem will break, and the limit state is attained.

The process of uprooting is more difficult to model than stem breakage because of the complexity of the interaction between the root system and the soil. As the tree's rotation increases due to wind loading, its own weight contributes to its instability, potentially leading to tree failure. Following the recommended constraints from pulling tests, an uprooting limit state corresponding to the maximum permissible rotation of 0.25 degrees at the base is defined. Furthermore, it is used as reference parameter in the numerical modelling. The model presented in this research could be validated using available tree-pull test data. The general workflow of the vulnerability estimation process, aimed at the investigation on the scenario-based attainment of limit states, is shown in Figure 2.

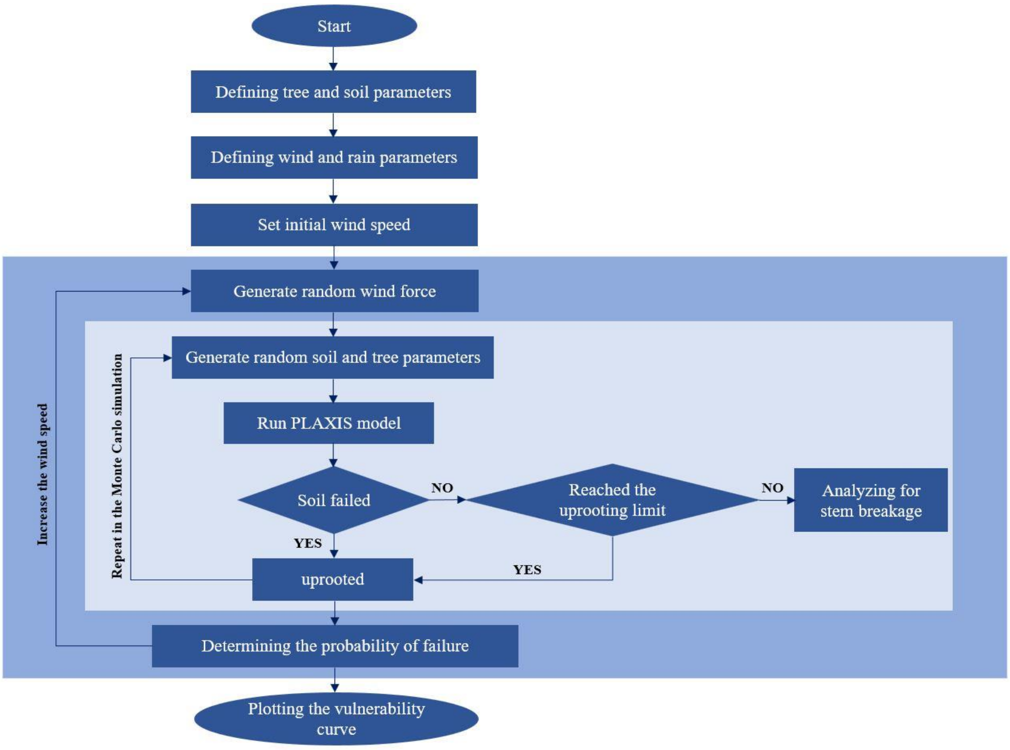

Figure 2: Vulnerability development procedure.

5 Summary and conclusions

The article illustrates the initial steps of a framework aimed at improving the risk-based management of trees under the effects of wind and rain. It demonstrates the potential of numerical modelling in evaluating the vulnerability of trees in terms of two relevant limit states related to stem breakage and uprooting. Further research will be conducted to refine the proposed model. Additionally, validation of the model using tree-pull test data will be conducted prior to real-world implementation of the methodology. The results of the research will hopefully support and improve decision-making processes related to the preservation and development of urban green spaces.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Definition of the multi-risk framework, M.S., M.U., I.D., G.B.; conceptual set-up of the numerical modelling, M.S., M.U., I.D., G.B.; original draft preparation, M.S.; revision, M.S., M.U., I.D., G.B.; supervision, G.B., I.D.; project administration, G.B.; funding acquisition, G.B. All authors have read and agreed to the published version of the manuscript.

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