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Discrete element model of the dynamic response of fresh wood stems to impact

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ABSTRACT

Forest stands are an efficient natural protection solution against rockfall. After windstorms or forest maintenance tasks, their protection capacity decreases. To compensate the loss of the protective function, a certain number of felled trees can be left on the slope as wooden protective structures. Studies are currently being conducted to estimate the efficiency of these devices and most particularly their resistance to block impacts and their energy dissipation capacity.

A numerical model based on the discrete element method is developed herein to describe the fresh wood stem's response to a dynamic loading. The fresh wood stem is modeled by a cylindrical beam composed of discrete elements. Studying the interaction between the elements makes it possible to describe the relation between bending moment and rotation accounting for the elasto-plastic response of the stem.

The numerical model is validated by comparing the predictions with analytical solutions. Then the model is calibrated using experimental data from quasi-static and impact laboratory experiments. The numerical approach provides an accurate description of the quasi-static and dynamic response of fresh wood stems. The mechanical properties of fresh wood stems are assessed from the model calibration results and are coherent with the data found in the literature.

1. Introduction

In mountain areas, significant investments have been made to protect inhabitants and infrastructures against natural hazards such as rockfalls. Civil engineers develop and optimize rockfall protection devices. However, the complexity of impact loadings, the interaction with projectiles, and the large displacements of the structure make the design of such devices a complex task. For this reason, numerical models based on the finite element method (FEM) have been intensively used for structure analysis and design. However, FEM simulations can become expensive in terms of computation costs when nonlinear behaviors and failure are integrated. Among the other numerical methods that can be used for structure design, the discrete element method (DEM) [1] is well adapted to easily describe large displacements, material nonlinearities, and contact interactions.

The DEM has already been extensively used for modeling rockfall protective structures: flexible metallic fences, e.g., [2–6], and embankments [7,8]. In particular, this technique can simulate the block's impact onto the structure accounting for the different physical processes involved.

In the field of rockfall protection engineering, most studies have investigated protective structures such as flexible metallic fences or embankments [3]. However, forest and bio-engineering devices also have a significant capacity to dissipate rockfall energy [9,10].

This study aims to develop, calibrate, and validate a numerical model of bio engineering rockfall protection devices made of trees. The final goal is to provide a numerical model of a protection device made of a felled tree considering their mechanical properties after setting up the structure and their evolution over time. In the first step, it is necessary to characterize the behavior of fresh wood stems under dynamic loading. The mechanical characteristics of fresh wood differ from the characteristics of dry wood given the differences in water content [11,12].

A numerical model of fresh wood stems based on the DEM is proposed to model bio engineering structures and their interaction with rockfalls. Block impacts are considered mainly orthogonal to the tree's longitudinal axis and occurring far enough from the supports, leading to reduced shear loadings. Thus, the study focuses on the characterization of the bending response of fresh wood stems under quasi-static (QS) or dynamic loadings. The numerical model

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was developed using the open-source code Yade-DEM [13]. Recent developments of this code have enabled modeling cylindrical bodies [14,15] and their interaction with bodies of different shapes (i.e., spheres, facets, etc.), which is useful for the modeling of wood stems and their interaction with blocks.

Numerical models allow exploring multiple real rockfall scenarii with acceptable costs in terms of CPU resources and computation time. However, their calibration and validation requires experimental data. Given the complexity of observing and analyzing rockfall impacts on protection devices in the field at a real scale, laboratory studies are a valuable solution to better control the different parameters and to obtain accurate data. Quasi-static and impact tests were therefore performed on small-diameter fresh wood stems (i.e., stem diameter <10 cm). The experimental results were used to calibrate the numerical model and identify the physical processes involved in the response of fresh wood stems subjected to impact.

2. Materials and methods

2.1. DEM model

The DEM consists in modeling the dynamic motion of a group of particles interacting by contact or remote interactions [1]. The sum of forces on each particle is calculated from the particles' location, orientation, geometry, and physical properties. An explicit numerical scheme is used in order to solve Newton's law at each timestep for each particle, allowing its position and orientation to be updated.

This method is well adapted to the study of granular materials and has been widely applied in this field [16,17]. However, the DEM can also be used to model deformable structures [15,4,5,18]. One of the key points to achieve accurate simulations is the implementation of appropriate interaction models between the discrete elements composing the structure.

In the proposed model, fresh wood stems are represented as deformable cylinders. These elements are modeled in the Yade-DEM code [13] as assemblies of spheres, called nodes hereafter, linked by cylindrical connections (Fig. 1) [14]. This approach makes it possible to differentiate the interactions between nodes (N), which govern the mechanical response of the deformable cylinder, from the interactions of the cylindrical connections (C) with external bodies, such as spheres. The latter can be used to model blocks for the study of the block–fresh wood stem interaction.

The study presented in this paper focuses on the stem's response to a given loading in an attempt to establish the appropriate formulation of the interaction model between adjacent nodes. The node interaction model is validated out focusing on the macroscopic stem behavior. The interactions of cylinders with external bodies are not considered in this study.

A local coordinate system (x_k, y_k, z_k) is associated with each node k $(k = 1 \ldots n)$, where n is the number of nodes. Initially, all

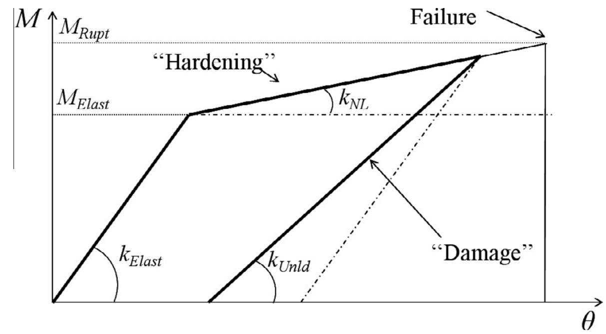

Fig. 2. Schema representing the trilinear hysteresis.

local coordinates systems are oriented similarly, with x_k along the stem's longitudinal axis, which is initially a straight line, and the vertical z_k axis oriented along Z (Fig. 1).

Interaction forces and moments are applied to the interacting nodes depending on their relative displacements and orientations following the approach described in [14].

In this paper, a multi-linear formulation is proposed to describe the bending moment (M_y or M_Z) between two adjacent nodes around the y_k or z_k axis, induced by changes in their relative orientation (θ_y or θ_z) (Fig. 2). The following study is reduced to one-dimensional loading and the bending moment and relative orientation are called M and θ, respectively. At each time step, the bending moment is applied to both interacting particles. This model is written within an incremental formulation.

For small relative orientations between the nodes, the bending moment increment (dM) can be related to the relative orientation increment (dθ) using the following linear relationship:

$$\mathrm{d}M = k_{Elast}\mathrm{d}\theta \qquad (1)$$

where k_{Elast} is a stiffness coefficient.

Eq. (1) is applied until a given bending moment (M_{Elast}) is reached. Then a different linear relationship between dM and dθ, associated with an updated stiffness coefficient (k_{NL}), is applied. Failure, which corresponds to the elimination of the node's interaction, occurs when the bending moment M_{Rupt} is reached. If this value is not achieved, the unloading process is also characterized by a linear relationship (Eq. (1)) between dM and dθ associated with an unloading stiffness coefficient (k_{Unld}) if the M_{Elast} threshold is achieved and k_{Elast} otherwise.

The stiffness coefficients k_{Elast}, k_{NL}, and k_{Unld} depend on the stem's geometry characteristics, distance between adjacent nodes (l), and the material's properties. A formulation proposed by Bourrier et al. [14] relates the stiffness coefficients to the interaction's geometrical and mechanical properties:

$$k_{Elast} = \frac{\mathrm{MOE}\,I}{l} \qquad (2)$$

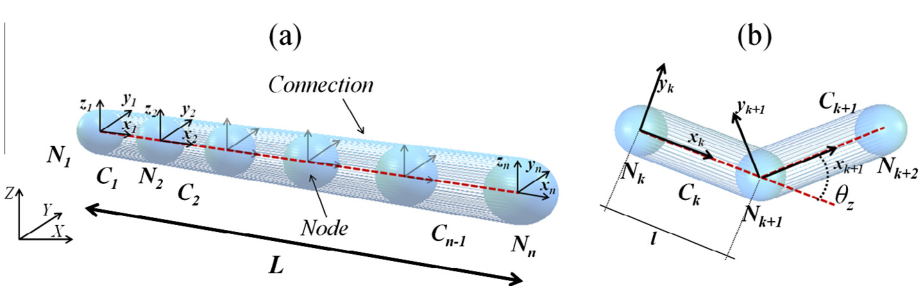

Fig. 1. (a) Grid elements made up of nodes (spheres) (N) and connections (cylinders) (C). l is the length of a connection and L is the total length of the cylinder. Global (XYZ) and local (x_k, y_k, z_k) coordinate systems are depicted. (b) Orientations of two adjacent nodes and the relative orientation θ_z around the z-axis.