International Journal of Impact Engineering 103 (2017) 76–89

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Discrete dynamic modelling of the mechanical behaviour of a granular soil

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A R T I C L E I N F O

Article History:
Received 10 September 2016
Revised 12 January 2017
Accepted 12 January 2017
Available online 13 January 2017

Keywords:
Rockfall
Impact
Granular material
Discrete element method
Kinetic energy

A B S T R A C T

This paper investigates the interaction between a falling rock boulder and a granular medium through numerical modelling based on a discrete element method. The boulder is modelled as a single sphere with an incident velocity, and the medium is modelled as an assembly composed of poly-disperse spherical particles. A classical elastic-plastic contact law is implemented with rolling resistance to consider the particle shape effects. The numerical modelling is validated by comparison with results from the literature in terms of impact force, impact duration and the boulder's penetration depth of the boulder. Then the model is used to investigate the energy propagation within the impacted medium as well as the boulder bouncing. The energy propagation processes are investigated by analysing the space distribution of kinetic energy, elastic strain energy and energy dissipation within the medium over time. The boulder bouncing occurrence is studied, varying the impact conditions in terms of medium thickness and boulder size. Relations between the bouncing of the boulder and the response of the granular medium are finally discussed.

1. Introduction

Rockfall is a major hazard in mountainous areas. Rockfalls initiate with the detachment of rock boulders from cliffs. After detachment, the boulders transit downhill along the slope through falling, bouncing, sliding and rolling. The level of exposure of elements at risk at the foot of rock detachment areas is generally estimated based on rockfall trajectory simulations [1]. When necessary, protection structures may be built to reduce the risk [2].

Among the various types of rockfall protection structures, some are composed of granular materials: rock sheds made up of a concrete structure covered by a cushion layer and rockfall protection embankments composed of gravels. The design of these structures should account for the dynamic loading resulting from the impact by the boulder, most often described in terms of impact force and boulder penetration [2–7]. The boulder-medium interaction has been addressed by analytical models (e.g. [8]), experiments (e.g.[4,9]) and numerical simulations (e.g.[4,10,11]). Nevertheless, the various available analytical formulae aiming at estimating the impact loading have been shown to result in high discrepancies [12], notably because these models were calibrated based on global measurements, obtained in specific impact and boundary conditions that cannot be generalized. In addition, these models are most often based on strong assumptions, which limit their reliability [2].

Moreover, boulder trajectory simulation is based on the estimation of the boulder-soil interaction at each impact point. This interaction leads to a change in the boulder trajectory and is often modelled using global coefficients in trajectory simulation tools [1,13]. Many references in the literature provide these coefficients, based on full-scale experiments on natural slopes, small-scale experiments in the laboratory or numerical simulations. The restitution coefficients appear to be highly variable and depend on the boulder incident trajectory and soil characteristics [14–20]. Both the rockfall trajectory prediction and the protection structure design therefore depend on the interaction of the falling boulder and the soil body, this soil being either constitutive of the natural slope or of a man-made structure. This boulder-soil interaction is highly complex because it depends on the boulder's kinematics (in particular boulder mass, velocity, trajectory inclination) and on the soil's mechanical and geometrical characteristics [9,10]. However, for either the design of protection structures or the modelling of the bouncing of a boulder, the current approaches have limitations in predicting the boulder-medium interaction in the sense that they do not account for the various mechanisms occurring in the soil during the impact. These mechanisms lead to large soil deformation, soil displacement, as well as energy transfer and dissipation, which modify the soil-boulder interaction.

These mechanisms and their consequences may be conveniently addressed using numerical simulation tools. Energy terms can be

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http://dx.doi.org/10.1016/j.ijimpeng.2017.01.009

tracked through numerical simulations, while it is nearly impossible to obtain such information from measurements during experiments [6]. Bourrier et al. [10] indicated that boulder bouncing is attributed to a second energy supply from the soil after the compression wave's round trip through the sample. However, the conclusion is drawn from 2D simulations. In addition, the relation between the bouncing of the boulder and energy propagation within the medium is still not well understood. Therefore, research-based investigations of a boulder impacting a granular medium in 3D conditions are required to fully understand the bouncing of the boulder as well as the response of the granular medium.

This paper investigates the boulder-medium interaction through a 3D numerical modelling approach. A simple case of a boulder vertically impacting a granular medium is considered. The objectives include investigating the energy propagation within the impacted medium as well as the bouncing of the boulder. Within this perspective, a boulder-medium impact model based on a discrete element method is developed. A specific impact case is analysed in detail to understand the overall impact process. Impact simulations with different boulder masses are conducted and compared with results from the literature to validate the model. Once the model has been validated, the impact behaviour of the medium and the boulder are investigated. Concerning the medium, the main focus is put on the energy transfer processes. As for the boulder, the bouncing occurrence is investigated, varying the boulder size and medium thickness. Boulder bouncing appears to be closely related to the energy process within the impacted medium. All the simualtions presented in this paper are conducted in 3D conditions.

2. Numerical modelling and model validation

2.1. Description of a reference work

To support the design of rockfall protection structures composed of gravels, Pichler et al. [8] conducted dimensionless analysis and found that the targeted quantities, such as impact force, penetration depth and impact duration, were proven to be functions of the boulder mass, boulder falling height and gravel indentation resistance. Based on this, experiments investigating rock boulders impacting gravel media were conducted. Those experiments were set to let rock boulders of approximately cubic shapes hit a granular layer with a face, an edge, or a tip. The masses of rock boulders were set up to 20 000 kg. The falling heights of the boulders were set up to 20 m. The granular medium was a trench 25 m long, 4 m wide, and 2 m deep, filled with wide-range-grained gravel. This gravel medium is commonly used for rockfall protection purposes in Europe. The volume fraction of fine, medium and coarse gravel (diameters ranging from 2 to 63 mm) was equal to 60%. The remaining volume fraction of 40% consisted of edged stones (diameters ranging from 63 to 200 mm). The trench was filled with gravel in 25-cm-thick layers. The mass density of the gravel was equal to 1800 kg/m^3. The experimental results were used to conduct back analysis to obtain the gravel indentation resistance. Based on this, the impact force, impact duration and penetration depth for impact situations beyond experimental measurements can be predicted to serve for the design of rockfall protection structures. The experiments conducted by Pichler et al. [8] are close to the simulation conditions considered in this paper, and the results predicted based on experimental data were used to validate the numerical model.

2.2. Contact law

A discrete element method (DEM) model was used to conduct the impact simulations. The DEM is now widely used to model the behaviour of granular materials (e.g.[10,21–25]). The DEM models granular materials as collections of particles. Therefore, the DEM is capable of modelling large deformations taking place within the impacted medium.

Discrete element modelling includes two types of simulations: contact dynamics and molecular dynamics. Contact dynamics assumes particles have no local deformation; the velocities of particles are discontinuous since no overlapping takes place between particles [26]. In the molecular dynamics method dealing with locally deformable particles, the calculation is composed of a series of calculation loops [27,28]. In each calculation loop, the contacts and positions of particles are first detected. The contact forces exerted on the particles are calculated based on the contact law (force-displacement law). Then Newton's second law of motion is used to update the positions and contacts of particles. Thus, the response of granular materials evolves with the calculation loops. The molecular dynamics method includes a much easier framework than contact dynamics approaches. On the other hand, there are small deformations on the particle surface under loading, which is acceptable when modelling the impact process. Moreover, the computation cost is less expensive using molecular dynamics when there is a large number of particles. Therefore, the molecular dynamics method is adopted in this paper.

To model granular materials involved in slope or rockfall protection structures, a DEM contact law composed of two components was adopted (Fig. 1). The first component is an elastic-plastic contact relation. The second component, rolling resistance, is implemented to consider particle shape effects.

The elastic-plastic contact law [29] first considers a linear relation between the inter-particle penetration $\overrightarrow{u_n}$ and the force in the normal direction $\overrightarrow{F_n}$:

$$\overrightarrow{F_n} = k_n \overrightarrow{u_n} \tag{1}$$

In addition, an elastic-plastic relation together with a Mohr–Coulomb criterion is considered in the shear direction. The incremental shear force $d\overrightarrow{F_s}$ is calculated as the shear stiffness k_s times the relative incremental shear displacement $d\overrightarrow{u_s}$:

$$d\overrightarrow{F_s} = k_s \, d\overrightarrow{u_s} \tag{2}$$

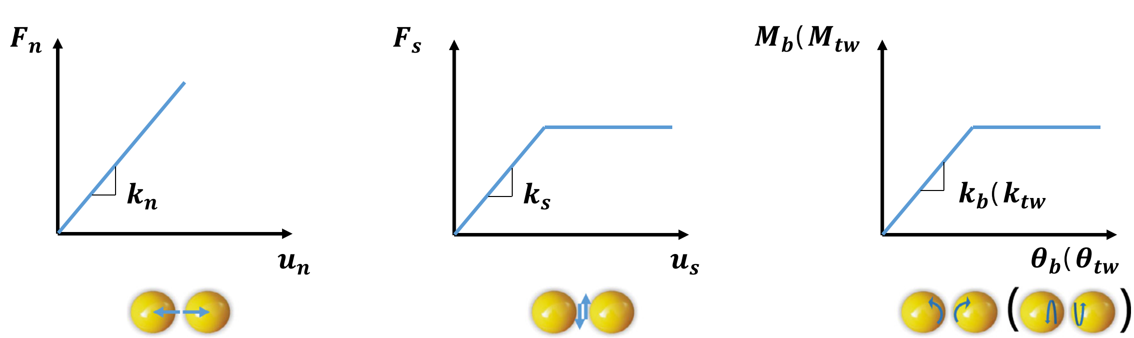

Fig. 1. Description of the contact model.