Simulations of non-stationary flows of dry granular material along an inclined chute

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Abstract. In this work, the signals generated by grain-to-base multiple impacts of three different granular materials flowing along an inclined chute and characterized by unsteady-state conditions are investigated through the discrete element method (DEM). The effect of different grain-size and angularity of the grains are taken into account. Various instants of the flows are studied, focusing in particular on the analysis of the signal produced by the passage of the material on a portion of the base of the chute, and on the study of the motion of the particles close to the base. The numerical results allow us to have an insight into the characteristics of the flows and to explain the behavior of the granular material at the contact with the base.

1 Introduction

In this work, the discrete element method (DEM) [1] is used to model an unsteady dry granular flow in a chute produced by a coarse material (i.e. gravel) and to investigate the signal transmitted to a portion of its base. DEM allows to study the kinematics of the whole mass as well as the single impacts between particles pairs and particles with the base. Differently from experimental tests, simulations can provide detailed information about the forces exchanged by the particles, their instantaneous velocities and the effect of micromechanical aspects on the overall behavior. Several literature works consider granular flows in steady-state regimes simulating small volumes with periodic boundary conditions [2] while few works were devoted to unsteady conditions even if the laboratory tests are mainly conducted in these conditions [3]. Most of the research works are conducted using simple spheres but the effect of different shapes was proved to play a relevant role in the emergency of different velocity profiles and wall friction [4].

The goal of the present study is to deduce the characteristics of the dynamics of the flows from the signal generated by different material flowing along a rigid chute with a smooth base and fixed slope angle. Results obtained with DEM simulations are compared focusing on the effect of different grain size and shape. Particularly rounded and sharp edges grains are considered by mimicking their real shape with rigid aggregates of spheres (i.e. clumps). The energy content and temperature of the granular flow is tracked along time in a monitoring volume close to the base of the chute as well as the corresponding basal forces.

2 DEM model parameters and simulations

A soft-sphere discrete element numerical approach was adopted, and in particular, the Hertz-Mindlin contact law, which comes from an approximation of Mindlin-Deresiewicz theory [5]. DEM simulations were run using the open-source framework for discrete elements Yade [6]. Three types of granular materials are considered as in [7], with different grain-size and roughness. Particle shape is discretized in DEM simulations through rigid aggregates of spheres, named clumps [8]. We synthetically report the material characteristics in Table 1.

Table 1. Material parameters.

	M1 (coarse gravel)	M2 (medium gravel)	M3 (medium gravel)
Particle angularity	Rounded	Rounded	Sharp
Mean diameter, d_{50} [mm]	19.7	12.4	12.6
Uniformity coefficient, C_u [-]	1.105	1.536	1.478

Numerical contact parameters accounted for the simulations are reported in Table 2 and are the same for the three materials considered M1, M2 and M3.

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Table 2. Numerical simulation parameters.

	Value
Contact friction angle, ϕ [°]	30
Normal restitution coeff., e_n [-]	0.9
Tangential restitution coeff., e_t [-]	0.9
Elastic contact modulus, E [MPa]	100
Poisson contact coeff., ν [-]	0.2

The geometry of the model is given by an upper retaining tank in which 22 kg of granular material are initially deposited; a flume 26.5 cm wide, 155 cm long and inclined of 40° with respect to the horizontal; a deposit box for the collection of the particles (Figure 1). The removal of the retaining gate that separates the deposit tank from the flume allows the granular material to flow along the chute. Data are collected only in a portion of the flume base – called monitoring plate – near its terminal part (1.5 m far from the position of the retaining wall). In this way, the plate is far enough from the release section to allow flow particles to break the force chains they develop in a static condition and to refer to a fully collisional regime.

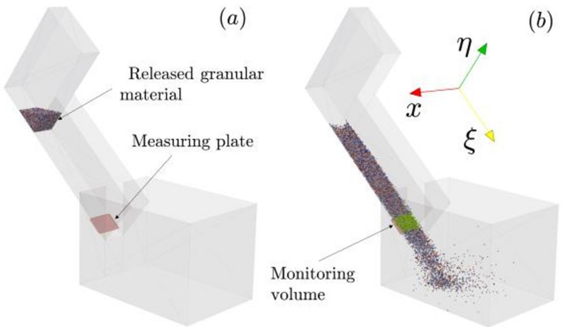

Fig. 1. Snapshots taken at different instants of the simulation: (a) view of the initial deposit of the granular material and (b) of the granular flow along the chute.

3 Numerical results

Results discussed hereafter stem from two different data-collecting methodologies: (i) data recorded on the monitoring plate (overall force components and interactions with the base); (ii) data recorded on a thin volume above the measuring plate containing the particles close to the base (individual kinematic quantities of the particles). Results for three materials at a fixed inclination of the chute are reported, thus allowing us to focus on the size and shape influence on the signal.

In the analyses presented, the following aspects are considered: (i) the time evolution of the forces exerted on the measuring plate, (ii) the time evolution of the energies and their weighted squared fluctuations (expressed as granular temperatures [9]) carried by the bodies near the measuring plate.

3.1 Time evolution of forces and energies

Once the deposited granular material is let free of flowing along the flume through the removal of the retaining wall, the recording of the signal begins at the entering of the particles in the monitoring volume, and it ends once all of them have transited on it. In Figure 2 the time evolutions of the longitudinal tangential force (F_ξ) and normal force (F_η) at the monitoring plate are reported for all three materials employed.

From the mere time history of the forces, a higher fluctuation of M1 with respect to the other two materials can be observed. This behavior can be explained by the coarser particles impacting on the plate. Besides, the size of the material influences the signal in terms of the mean forces that it exerts on the base: the coarser the material, the higher the forces it transmits to the base of the flume.

On the other hand, an effect due to the shape can be identified from the duration of the event: from Figure 3 it can be observed that particles with the same sizes but different shapes (materials M2 and M3) take different time to travel through a section (in our case a monitoring volume) of the chute: as expected, the flow is slower when the granular material is characterized by sharper edges. The duration of the event, on the contrary, doesn't seem to be influenced by the dimension of the particles, as materials M1 and M2, take the same time to transit on the monitoring volume. This can be viewed as indirect proof of the negligible effect of the width of the flow in these conditions [10].

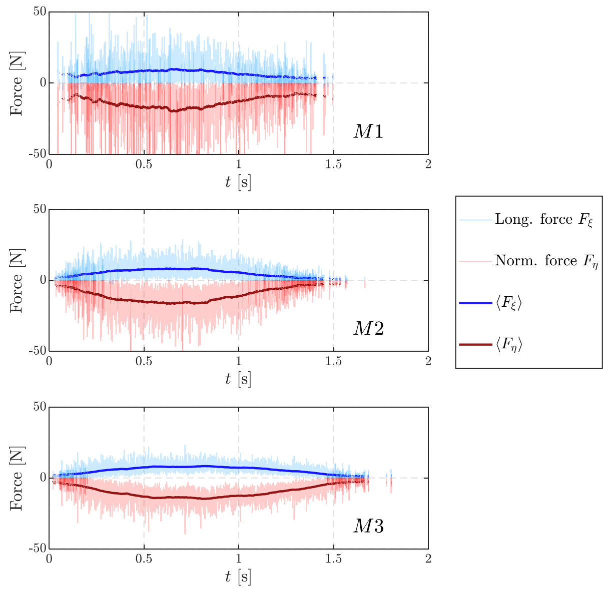

Fig. 2. Time evolution of the normal and tangential forces exerted by the granular flow on the measuring plate for the three materials.

Both total kinetic energy (E_k^{TOT}) and mass (m^{TOT}) evolutions with time are reported for the three materials, as can be seen in Figure 3. From Figure 3a the E_k starts to grow up to a maximum value but for none of the three flows a stationary condition is reached. After that a decreasing trend can be observed with a lower steepness than the previous one.

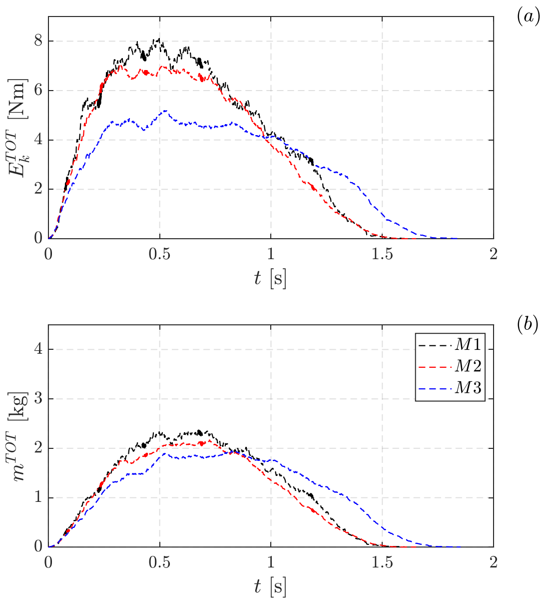

Fig. 3. Time evolution of (a) the total energy and (b) the mass of the particles above the monitoring area.

The rounded edge particles have a total kinetic energy higher than sharp edge particles, as can be seen in Figure 3a; whereas the energy peak instant is reached more or less simultaneously for all materials. The mass trends present their respective peaks with a delay in comparison to energy. This behavior had been observed for the same materials in [7] with a shorter and wider flume.

3.2 Granular temperature of the particles close to the base

In order to examine more deeply the energetic content of the flow, particularly in its portion in the immediate proximity to the basal surface, granular temperature [9] components are investigated. Assuming a further subdivision of the monitoring volume with the elevation η, and considering the lowest one (hereinafter called basal volume), from the kinematic characteristics of the clumps embedded in such a volume, the components of the granular temperatures are obtained. In Figure 4 the particles within the basal volume are depicted and, among them, those in contact with the base are indicated.

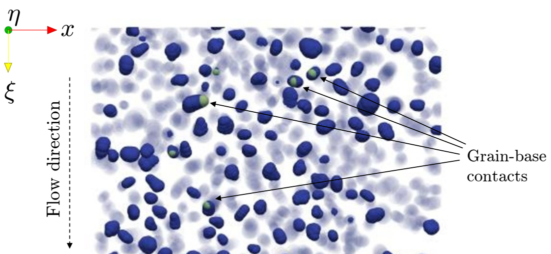

Fig. 4. Grain-base contacts visualization from bottom of the chute

The granular temperature components T_{trans} (Eq. 1) and T_{rot}, express the square of the fluctuation velocity component considered with respect to a mean value, obtained for all particles within the basal volume at a given instant.

$$T_{transl} = (T_{transl_{xx}} + T_{tansl_{\xi\xi}} + T_{transl_{\eta\eta}})/3 \quad (1)$$

$$T_{transl_{ij}} = \langle v_i v_j \rangle - \langle v_i \rangle \langle v_j \rangle \quad (2)$$

where $i, j = \{x, \xi, \eta\}$.

Figure 5a shows how the shape of the particles has an influence over T_{transl}: for sharp edge particles M3 the time trend is significantly different to the ones of materials M1 and M2. In Figure 5b the T_{rot} component is reported. From the comparison of the signals, both granulometry and angularity of the material seem to play a role over this quantity.

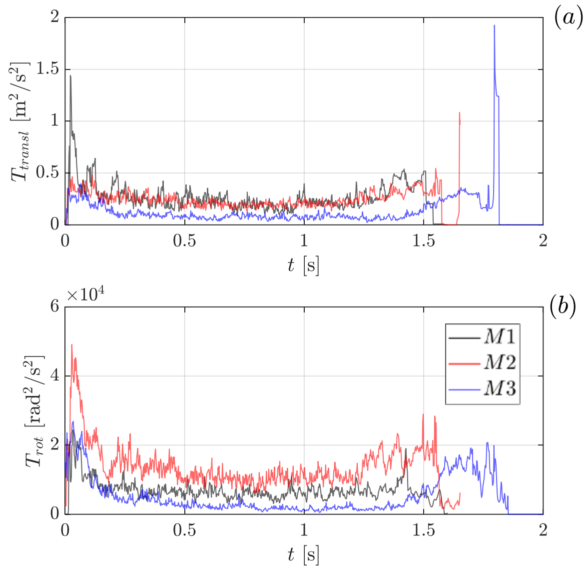

Fig. 5. Time evolution of (a) translational and (c) rotational granular temperatures in the basal volume.

Further conclusions can be drawn considering the ratio between rotational and translational kinetic energy components in the basal volume, as presented in Figure 6. We have a monotonic increasing trend for rounded particles with higher fluctuations for the coarser grain fractions; for sharp particles the trend is different, as it decreases throughout time, with the exception at its tail: only at the final instants of the flow are the particles sufficiently sparse to be able to rotate freely at the base.

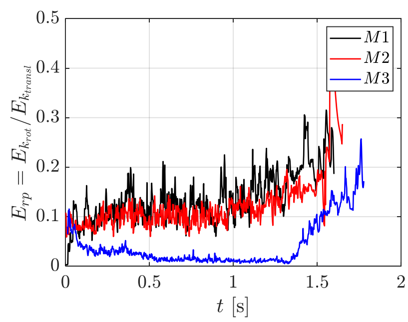

Fig. 6. Time evolution of the ratio between rotational and translational kinetic energy components for the three materials in the basal volume.

4 Conclusions

In this work, a numerical study through DEM of non-stationary flows characterized by different granulometry and grain angularity is presented. Investigating the forces transmitted to the base of a monitoring volume and the kinetic properties of the particles in proximity to it, we were able to assess the effect of the shape and size of the granular materials on the type of signal generated.

DEM easily provides in-depth information about kinematics of each particle and contact forces between particle pairs and at particle-base contact. The energy content of the particles of the flow in proximity to the base can be gathered as well as the fluctuation of the forces and in their average values with time.

From the comparison of the signal generated by the three reference materials, we can observe that the particle shape affects the normal and tangential force fluctuations at the base and its mean value. The granular mass is more elongated along the chute for sharper particles and consequently the transit time results longer. The energy content of the flow is lower considering sharp edge particles as well as the granular temperature in a volume close to the monitoring plate.

For what concern the particle size, the larger the grains are, the higher the force fluctuations and mean values. On the other hand, the grain size seems to play a minor role in the energy of the flow and its granular temperature.

Acknowledgments

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