Impact of Dry Granular Flows on a Rigid Wall: Discrete and Continuum Approach

Original Citation:

Availability:
This version is available at: 11577/3209951 since: 2018-06-19T16:59:03Z

Publisher:
Elsevier Ltd

Published version:
DOI: 10.1016/j.proeng.2016.08.421

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 158 (2016) 152 – 157

Procedia Engineering

www.elsevier.com/locate/procedia

VI ITALIAN CONFERENCE OF RESEARCHERS IN GEOTECHNICAL ENGINEERING –
Geotechnical Engineering in Multidisciplinary Research: from Microscale to Regional Scale,
CNRIG2016

Impact of dry granular flows on a rigid wall: discrete and continuum approach

Fabio Gabrieli[a],*, Francesca Ceccato[a]

[a]*DICEA, via Ognissanti 39, 35129 Padova, Italy*

Abstract

Numerical simulations of impacts of granular flows with structures are complex because they have to take into account large deformations, large strain rates and interactions with boundaries or structures. Moreover, the material response is governed by interactions between grains, which leads to a complex rheology. Discrete methods (DEM), which apply a micromechanical approach, appears very well suited to this purpose, but they can hardly deal with large-scale problems. In contrasts, continuum methods can handle large granular volumes because they use a macroscopic approach in which the material behaviour is described by a constitutive model. The aim of this paper it to compare the results obtained by a discrete and a continuum approach in simulating the impact of a dry granular flow on a rigid wall. The problem is simulated with a DEM code and with a software based on the Material Point Method.

Peer-review under the responsibility of the organizing and scientific committees of CNRIG2016

Keywords: granular flow; MPM; DEM; impact forces

---

1. Introduction

Granular flows have been classified as one of the most hazardous landslides due to their high velocities and impact forces, the long run-out distance and the poor predictability. Protective structures, such as retaining walls, fences, and dams, can be installed to slow down or stop granular flows from affecting adjacent infrastructures and residential communities. The impact forces exerted by a granular flow are computed with simplified methods. A numerical tool

---

* Corresponding author. Tel.: +39 049 827 7993.
E-mail address: fabio.gabrieli@unipd.it

Peer-review under the responsibility of the organizing and scientific committees of CNRIG2016
doi:10.1016/j.proeng.2016.08.421

able to capture the key features of these phenomena would be useful in the design of structures that can withstand snow and rock avalanches as well as high-speed landslides. Most studies of dry granular flows in the context of geo-hazards focused on flow models for predicting the run-out distance, velocity, and other variables. The understanding of the impact process and the evolution of the static and dynamic force components are still quite limited.

Numerical simulations of granular flows are complex because they have to take into account large deformations, large strain rates, interactions with boundaries or structures, and collisional interactions between grains, which leads to a complex constitutive behavior of the material. Various numerical techniques have been used for analyzing the inception or the propagation of a landslide, but only a few are suitable for studying the whole process as well as the impact against structures. These include Discrete Element Methods (DEM) [1], and continuum-based Lagrangian meshless methods [2–4].

DEM applies a micromechanical approach (single soil grains are simulated). The interactions between grains is taken into account realistically, but the knowledge of the contact parameters, their link to macroscopic quantities and the effect of considering grain-shapes different than spherical can be difficult to determine. The computational cost is very high, thus simulations of real-scale events may be ineffective. For this reason, continuum-based methods are often preferred. They apply a macroscopic approach, in which the behavior of the granular mass is described by the constitutive model. Lagrangian meshless methods can simulate small and large deformations of big soil masses with a limited computational cost. Amongst them, the Material Point Method (MPM) appears to be particularly promising and it is preferred in this study.

The aim of this paper is to compare the results obtained with a discrete and a continuum approach in simulating the impact of a granular flow on a rigid structure. In this work, we consider a set of laboratory tests reported by [5]; in which a cubical sample of dry granular material is instantly released from the top of an inclined slope, it flows down the channel and hits a rigid wall on which impact forces are measured. Two reference tests have been selected varying the chute inclination (θ = 30° and θ = 40°). The problem is simulated using DEM (discrete approach) and MPM (continuum approach). The considered problem is very complex; an exhaustive comparison between the two methods, covering all the similarities and dissimilarities, exceeds the purpose of this paper, which wants to give only an insight to the problem.

2. DEM model

The Discrete Element Method is used to simulate the behavior of granular materials in several fields: from geotechnics, to material science and process engineering. It explicitly solves the dynamic of discrete interacting particles by assuming a micromechanical constitutive model at the contacts. In our case the basic contact model has been used: the normal contact is ruled by a linear elastic spring coupled with a dashpot while a frictional slider, a dashpot and a linear spring is used in tangential direction [6]. Frictional parameters have been selected on the base of the measurements given in [5]. Linear elastic stiffness parameters at the contact have been chosen according to the calibration performed in [7]. Damping coefficient has been computed on the base of restitution coefficients provided in the same publication. Grain-size used in simulations is similar to the experimental tests and has been obtained linearizing the grain size distribution around a mean value d_{50} = 14.1 mm (finest and coarsest particles were neglected). It is worth to note that microscopic friction coefficient is not the real one because the shape of each grain was simplified with a sphere that is free to rotate. Some preliminary tests have shown that its effect on the result is quite negligible, and the macroscopic friction angle was then adopted. The parameters used in DEM simulations are listed in Table 1.

Table 1. Material parameters used in DEM simulations.

Grain density (ρ_s)	2650 kg/m^3	Interparticle friction angle (φ)	53°
Porosity (n)	0.48	Mean diameter (d_{50})	14.1 mm
Normal contact stiffness (k_n)	400 kN/m	Basal friction coefficient (μ_b)	0.466
Tangential contact stiffness (k_s)	100 kN/m	Retaining wall friction coefficient ($\mu_{w,r}$)	0.384
Norm. and tangential viscous damping coeff. (c)	0.3	Lateral wall friction coeff. ($\mu_{w,l}$)	0.268
Grain-size ratio d_{min}/d_{max}	2		

The initial granular sample is generated in a cubical box by randomly placing a suitable number of particles with the same grain size as reported in experiments [5] and applying gravity until a stable condition has been reached. The final sample resulted slightly taller than the real one because we preferred to match the initial mass of the experimental tests and to relax volume and porosity constraints which are inevitably different replacing the real particles with the spheres. Then the channel is inclined to the prescribed angle and the lateral wall is instantaneously removed.

3. MPM model

The MPM is a particle-based method specifically developed for large deformations of history dependent materials [8]. It has been successfully applied to the simulation of a number of geotechnical problems such as slope stability [9], pile installation [10,11], and impact of granular avalanches on rigid obstacles [4].

The continuum body is discretized by a set of Lagrangian points, called material points (MPs), which carry all the information of the continuum. The MPs do not represent single soil grains, as in DEM, but a portion of the continuum body. Large deformations are simulated by MPs moving through a fix computational finite element mesh that covers the entire region of space into which the solid is expected to move. This grid is used to solve the system of equilibrium equations, but does not deform with the body like in Lagrangian Finite Element Method.

The MPM code used in this study (Anura3D) is being developed to solve 3D dynamic large deformation problems in geotechnical and hydromechanical engineering [12]. Soil-structure interaction and frictional sliding are simulated by a contact formulation based on Coulomb's law [13].

The geometry and discretization of the problem are shown in Figure 1. Anura3D allows only 3D models, but the considered problem is bidimensional; to reduce the computational cost, the width of the channel is reduced to 2.5cm. The material behaviour is described with an elastic-perfectly plastic model with Mohr-Coulomb failure criterion. The constitutive parameters are listed in Table 2; they are derived from the experimental test published in [5].

Table 2. Material parameters of MPM model.

Grain density (ρ_s)	2650 kg/m^3	Friction angle (φ)	53°
Porosity (n)	0.48	Cohesion (c')	0
Young modulus (E)	50 kPa	Basal friction coefficient (μ_b)	0.466
Poisson's ratio (ν)	0.25	Wall friction coefficient (μ_w)	0.384

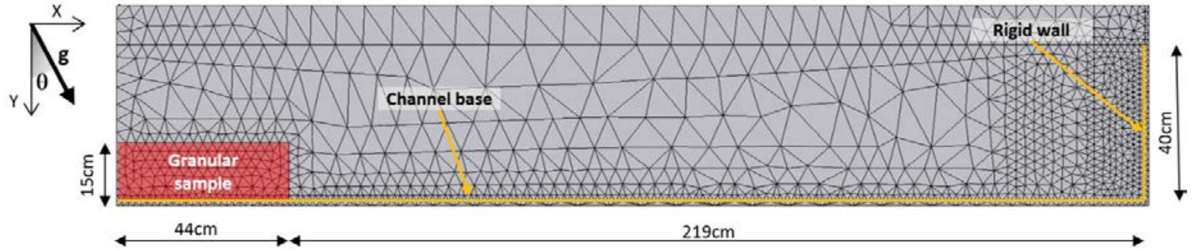

Fig. 1. Geometry and discretization of the 3d MPM model. It counts 7438 elements and 18251 MPs. Note that the gravity vector is inclined.

4. Results

Differences between the continuum and the discrete approach appears already in the generation of the initial configuration: in MPM the material is initially confined in a regular rectangular box, while in DEM the upper surface of this volume is taller, irregular and slightly curved because of the method used to generate the sample (see Section 2.1) (Fig. 2). During the initiation of motion, in DEM the mass seems to deform homogeneously while in MPM a wedge in the front of the sample shows a larger displacement than the rest of the material (Fig. 3).

During the propagation the mass elongates, and the front inclination reduces in both methods. The thickness of the flow is similar in DEM and MPM but its length is larger in DEM because of higher velocities at the front (Fig 4).

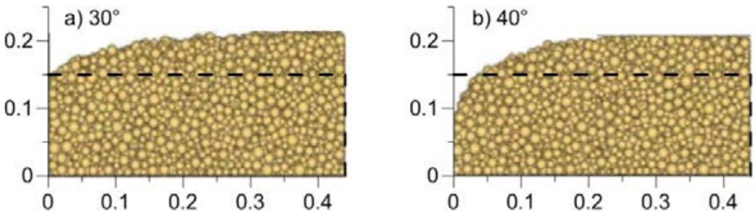

Fig. 2. Comparison between the shape of the initial mass in DEM (yellow spheres) and MPM (dashed line) for (a) θ = 30° and (b) θ = 40°.

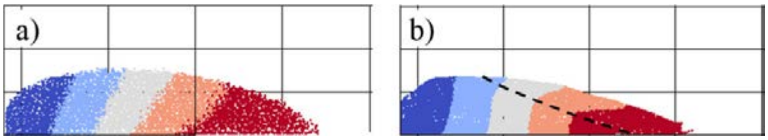

Fig. 3. Deformed sample at time t = 0.24 s obtained with (a) DEM (b) MPM.

The flow reaches the obstacle earlier in DEM than in MPM, meaning that the velocities are higher in the first case. When the flow hits the barrier, it is projected upwards thus increasing the height of the mass stressing the wall. When the material decelerates a dead zone forms, which attenuates the effect of the dynamic impact on the rigid barrier. The formation of the dead zone is different in the two methods. Figures 5c and 5d show the evolution of the flow profile during the impact in case of θ = 40°. We can observe that in DEM, the profiles are very steep in comparison to the MPM. It seems that in DEM the first particles hit and climb the wall forming a sort of damper for the incoming grains. Coloring the mass with vertical color bands in a time step just before the impact (Fig. 5a-b), we can observe the main deformation occurred to each vertical strip after the impact (Fig. 5c-d). In DEM the strips mainly experience a compression normal to the wall while in MPM they show a prevalent shear distortion. As a result, the initially vertical bands become convex with respect to the wall in DEM and straight but inclined in MPM. Similar observations are also valid for θ = 30°.

Figure 6 shows the normal impact forces obtained with the two models. With both methods, in case θ=30° the force increases up to a constant value, which corresponds to the static reaction force. In case θ=40°, the force increases up to a peak value due to the dynamic impulse and then decreases to the constant static value. However, the impact forces are quantitatively different in the two methods.

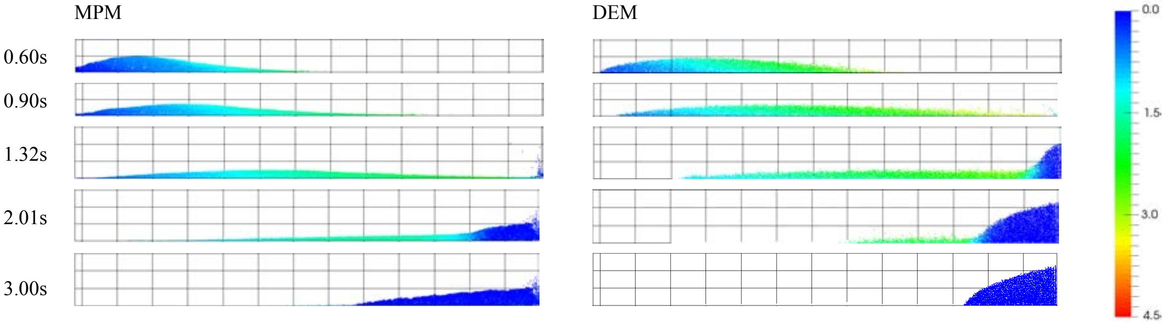

Fig. 4. X-velocity field during the propagation and impact phase in case of θ = 30°.

MPM predicts lower impact forces in case of slope inclination θ=30°. This result is explained observing the shape of the dead zone: in MPM simulation the deposit is thinner and more elongated compared to DEM (Fig. 4). In contrast, a higher peak force is obtained with MPM for the inclination of 40°. This result may be surprising because the impact velocities are higher in DEM. It could be due to the different evolution of the dead zone or to a different behavior of the material attributed during the impact by the continuum and discrete approach. Indeed, it can be noted that in DEM the front is characterized by a collisional regime: the density is quite low and particles interact mainly by instantaneous collision with a significant energy dissipation, which is not taken into account in the continuum approach.

The maximum impact force measured in the experiment is 0.3kN/m for θ=30° and 0.8kN/m for θ=40°. Both methods overestimate the impact force, but it seems that a better result is obtained with MPM at low inclinations, and with DEM at higher inclinations.

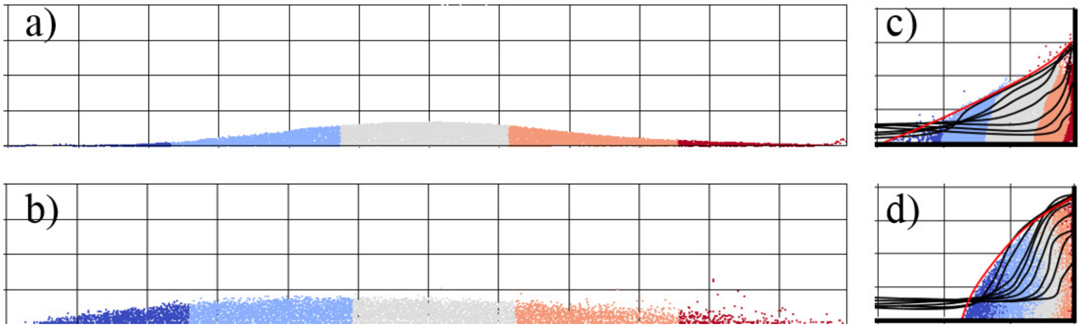

Fig. 5. Flow profile before the impact in (a) MPM and (b) DEM and flow profile evolution during the impact for (c) MPM and (d) DEM.

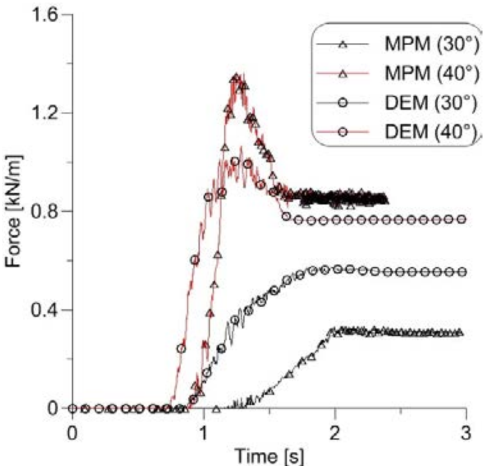

Fig. 6. Normal impact forces obtained with MPM and DEM for inclination angles of 30° and 40°.

5. Discussion and conclusions

The impact of a granular mass is a complex phenomenon, which is the result of multiple phases correlated one each other: the initiation of motion, its propagation along the channel and the interaction with the obstacle with the subsequent formation of the dead zone. In this work, we did not cover exhaustively all these aspects but we want to give an insight to the problem.

Although the two methods are intrinsically different, the obtained evolution of the impact force is qualitatively similar, but not quantitatively. The impact force is strongly influenced by the evolution of the dead zone which acts as a damper for the arriving flow mass. The formation of the dead zone differs between DEM and MPM thus explaining the dissimilar force values.

DEM takes into account the micromechanical interactions between particles, which appears fundamental to describe the behavior of dense granular flows. In particular, the number of collisions and the evolution of the force chains should be investigated. In DEM solid grains are simulated with spheres but true granular matter is constituted by irregular angular particles; the effect of the shape and the contact model should be examined in more details.

In MPM the material response is simulated with an elastoplastic model, which is unable to take into account the effect of instantaneous collisions between grains. To improve the results, a more sophisticated constitutive model, able to capture the behavior of the granular flow in a wide range of shear rates, should be implemented. However, despite the research done in this field, a satisfactory solution has not be found yet.

Acknowledgement

The authors would like to thank the EU and the Italian Ministry of Education, University and Research (MIUR) for funding, in the frame of the collaborative international consortium DOMINO financed under the ERA-NET Cofund WaterWorks2014 Call. This ERA-NET is an integral part of the 2015 Joint Activities developed by the Water Challenges for Changing World Joint Program Initiative (Water JPI).

References

[1] A. Leonardi, F.K. Wittel, M. Mendoza, H.J. Herrmann, Coupled DEM-LBM method for the free-surface simulation of heterogeneous suspensions, Comput. Part. Mech. 1 (2014) 3–13. doi:10.1007/s40571-014-0001-z.

[2] N. Prime, F. Dufour, F. Darve, Solid – fluid transition modelling in geomaterials and application to a mudflow interacting with an obstacle, Int. J. Numer. Anal. Methods Geomech. 38 (2014) 1341–1361. doi:10.1002/nag.

[3] H. Bui, K. Sako, R. Fukagawa, J. Wells, Sph-based numerical simulations for large deformation of geomaterial considering soil-structure interaction, in: 12th Int. Assoc. Comput. Methods Adv. Geomech., Goa, India, 2008. http://www.civil.iitb.ac.in/~dns/IACMAG08/pdfs/A70.pdf (accessed September 27, 2013).

[4] C.M. Mast, P. Arduino, G.R. Miller, P. Mackenzie-Helnwein, Avalanche and landslide simulation using the material point method: flow dynamics and force interaction with structures, Comput. Geosci. (2014) 817–830. doi:10.1007/s10596-014-9428-9.

[5] Y.J. Jiang, I. Towhata, Experimental study of dry granular flow and impact behavior against a rigid retaining wall, Rock Mech. Rock Eng. 46 (2013) 713–729. doi:10.1007/s00603-012-0293-3.

[6] P. Cundall, O. Strack, The development of constitutive laws for soil using the distinct element method, Numer. Methods Geomech. (1979) 289–317. https://scholar.google.it/scholar?q=DEM+cundall+1979&btnG=&hl=it&as_sdt=0%2C5#0 (accessed May 4, 2015).

[7] A. Albaba, S. Lambert, F. Nicot, B. Chareyre, Relation between microstructure and loading applied by a granular flow to a rigid wall using DEM modeling, Granul. Matter. 17 (2015) 603–616. doi:10.1007/s10035-015-0579-8.

[8] D. Sulsky, Z. Chen, H.L. Schreyer, A particle method for hystory-dependent materials, Comput. Methods Appl. Mech. Eng. 118 (1994) 179–196.

[9] K. Soga, E. Alonso, A. Yerro, K. Kumar, S. Bandara, Trends in large-deformation analysis of landslide mass movements with particular emphasis on the material point method, Géotechnique. 66 (2016) 248–273. doi:10.1680/jgeot.15.LM.005.

[10] F. Ceccato, L. Beuth, P.A. Vermeer, P. Simonini, Two-phase Material Point Method applied to cone penetration for different drainage conditions, in: Geomech. from Micro to Macro - Proc. TC105 ISSMGE Int. Symp. Geomech. from Micro to Macro, Cambridge, 2015: pp. 965–970.

[11] N.T.V. Phuong, A.F. van Tol, A.S.K. Elkadi, A. Rohe, Numerical investigation of pile installation effects in sand using material point method, Comput. Geotech. 73 (2016) 58–71. doi:10.1016/j.compgeo.2015.11.012.

[12] ANURA3D, (2016). http://mpm-dredge.eu/.

[13] S.G. Bardenhagen, J.E. Guilkey, K.M. Roessig, J.U. Brackbill, W.M. Witzel, J.C. Foster, An improved contact algorithm for the material point method and application to stress propagation in granular material, C. - Comput. Model. Eng. Sci. 2 (2001) 509–522.