Impact of a dry granular flow against a rigid wall: MPM simulations with a new constitutive approach

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Abstract. The dynamic interaction between granular flowing masses and obstacles is a very complex phenomenon involving large displacements and high strain rates. To simulate the event in a continuum-based framework both advanced numerical tools and constitutive relationships are required. In this work, the impact of a dry granular mass against a rigid wall is numerically simulated using the open-source Material Point Method code ANURA3D, while the constitutive model proposed by Marveggio et al., 2021 is adopted for the granular mass. The model accounts for rate and grain packing dependence, which have been shown to be crucial to reproduce the propagation of compression and rarefaction waves inside the mass. The model is capable of reproducing “solidification” and “liquefaction” phenomena observed in the DEM impact tests results already available in the literature.

1 Introduction

Risk mitigation measures for flow-like landslides are aimed at protecting the territory by modifying the propagation phase, which is by deviating/arresting the flowing mass. In particular, one popular strategy consists of protecting lifelines or buildings by installing concrete/earth retaining walls. The design of these mitigation works requires the definition of the force exerted on the structure by the impacting mass. Up to now, practical design applications are based on simplified equivalent pseudo-static approaches, which completely disregard the evolution of the interaction mechanism with time[1].

To improve the design technique, continuum-based approaches can be adopted to simulate the impact, by means of numerical tools suitable for large displacements analyses. In particular, Ceccato et al. [2] and Cuomo et al. [3] have shown the Material Point Method (MPM) to be a promising approach to simulate such a dynamic interaction. In their work, to reproduce the mechanical behavior of granular assemblies, the authors consider simple constitutive laws (elastic-plastic Mohr Coulomb non-dilatant relationships) in which strain-rate and grains packing dependence are disregarded. Nevertheless, these have been demonstrated to be dominant when describing the volumetric response and the fluidification and re-solidification mechanisms (“solid-fluid phases transition”) occurring under dynamic conditions [4,5,6].

In this work, the impact of a dry polydisperse granular mass on a rigid wall has been numerically simulated by means of the open-source code ANURA3D, which is based on a dynamic explicit MPM formulation. To this aim, since the discussion is limited to dry conditions, a single point formulation has been considered [7]. The novelty of this approach consists in the use of the constitutive model proposed by Marveggio et al. [8], which has been conceived to interpret solid-fluid phases transitions that occur during fluidification/solidification processes taking place during the arrest of a flow-like landslide [1].

The reliability of the MPM results is discussed by comparing the results with those of Redaelli et al. [9], who numerically simulated the phenomenon adopting a Discrete Element Method based code. The aim of this work consists in trying to numerically reproduce the mechanical processes taking place when a dry granular mass impacts against a rigid wall in a continuum-based framework. The use of the advanced constitutive model seems to be a promising approach to reproduce (i) the temporal evolution of the impacting force, (ii) the propagation of compression and rarefaction waves that induce solidification and liquefaction in the granular mass, after the impact takes place and (iii) the volumetric behavior associated to phase solid-to-fluid (and viceversa) phase transitions.

2 The numerical model

The numerical simulations are conducted considering the same scheme proposed by Calvetti et al [10]: the impacts is simulated by generating prismatic granular mass with vertical front of length L, height h impacting on a vertical rigid wall and sliding over a horizontal rigid base. It is assumed that, at the initial instant of time, corresponding...
to the time just before the impact, the mass is characterized by an initial uniform velocity $u_0$ and porosity $n_0$. Plane strain conditions are imposed. The rigid bodies, that are the wall and the base, are modelled according to Zambrano-Cruatty and Yerro [11]. Frictional contacts ([12]) between both the mass and the base ($\mu_b$) and the mass and the wall ($\mu_w$) are introduced. Gravity is applied to the material at the initial instant of time. To be consistent with DEM numerical simulations of Redaelli et al. [9], adopted as a comparison, an initially nil state of stress for the flowing mass is considered.

![Fig. 1. Impact scheme](image)

The same flow height $h=3m$, base friction coefficient $\mu_b = 0.3$ and obstacle friction coefficient $\mu_w = 0.6$ adopted by Redaelli et al. [9], are assigned, whereas the length $L$ has been assigned equal to $15m$. The mechanical behavior of the flowing mass is simulated by considering the strain hardening visco-elastic-plastic model, based on the critical state concept and kinetic theories of granular gases, proposed by Marveggio et al. [8]. Model parameters have been calibrated on DEM triaxial tests (both in compression and in extension) performed on specimens characterized by the same parameters employed in Redaelli et al. [9], considering different confining pressure and relative densities.

### 3 Numerical results

The capability of the numerical model to reproduce DEM impact tests has been here tested for a unique reference configuration characterised by $n_0=0.45$ and $u_0$ ranging between 2 and 12 m/s (the reference value is 8 m/s). The comparison between DEM and MPM numerical results in terms of horizontal force exerted by the mass on the wall is quite satisfactory (Figure 2). With respect to DEM results, MPM results present oscillations with a lower amplitude and which decays faster. This seems to be associated to the pathological numerical dissipation and viscosity typical of MPM approaches compared to traditional Lagrangian methods [13].

![Fig. 2. Temporal evolution of the impact force $F$: comparison between DEM and MPM predictions](image)

As already observed by Calvetti et al., 2019, by analyzing the fields of particles velocities and force chains in numerical DEM results, after the impact, the propagation of compression and rarefaction waves occurs inside the granular mass. These can be easily identified even in MPM numerical results by looking at the spatial and temporal evolution of the mean effective pressure inside the impacting mass (Figure 3). After the impact, a compression wave propagates horizontally (Figure 3a). This induces a significative increase in the mean effective stress. Then, a rarefaction wave starts to propagate from the top to the bottom of the mass, inducing a considerable reduction in the mean effective stress (Figures 3b and 3c).

![Fig. 3. Mean effective pressure distribution inside the granular mass at a) 0.01s, b) 0.07s and c) 0.1s](image)
4 Conclusions

In this work, the impact of a dry granular mass against a rigid wall is simulated using the MPM open-source code ANURA3D. The comparison between MPM and DEM results put in evidence the capability of the constitutive model proposed by Marveggio et al. [8] to simulate a highly dynamic process involving high strain rates and solid-fluid (and viceversa) phases transitions associated with the propagation of compaction and rarefaction waves, inside the medium. The results obtained suggest that the proposed approach represents a promising tool for sheltering structure design improvements, in terms of structure input load and prompt the authors in applying the same approach for larger ranges of initial velocities, porosities as well as geometries.

References