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Dry granular flows impacts on rigid obstacles: DEM evaluation of a design formula for the impact force

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Abstract

In the design of sheltering structures or embankments for the mitigation of the risk due to rapid and long spreading landslides, a crucial role is played by the evaluation of the impact force exerted by the flowing mass on the artificial obstacle. This paper is focused on this issue and in particular on the evaluation of the maximum impact force on the basis of the results obtained by performing an extensive numerical campaign by means of a 3D discrete element code (PFC3D), in which a dry granular mass is represented as a random distribution of rigid spherical particles. The analyses regard the impact process only, while triggering and the propagation phase of the flow are not considered. For this reason, in the model the granular mass is generated just in front of the obstacle; its initial volume, velocity distribution, height, length and porosity are assigned as initial conditions. The initial conditions are varied to take into consideration a large variety of geometrical/mechanical factors, such as the initial front inclination, its height, the initial void ratio, the length of the impacting mass and the inter-particle friction angle. A design formula is also proposed on the base of the obtained results and critically compared with the literature data and previous formulations based on hydrodynamic models.

Keywords: Discrete Element modeling; dry granular flows; impacts; impact force; rigid barriers; design formula

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1. Introduction

In the design of sheltering for rapid landslide risk mitigation pseudo-static approaches are very often employed. According to these approaches the maximum impact force (MIF) is estimated by using empirical formulae and is quasi-statically applied to the barrier without taking into account time evolution of the force. Moreover, the mentioned formulae are based on the adaptation of hydrostatic, hydrodynamic or deformable body models, through the use of empirical correcting factors. Very recently, in order to highlight and overcome the limitations of these approaches, the authors have performed a series of simulations using a Discrete Element 3D model. The aim of the simulations is to investigate the influence of the factors that determine the impact force, namely the geometry of the sliding mass (length, width and flow height, inclination of the front) and the impact velocity [1].

2. DEM model

The granular mass is assumed to be dry and is represented by an assembly of particles (Fig. 1) whose properties are listed in Table 1. The obstacle is represented by a vertical wall, and plain strain conditions are imposed by confining the flow between two smooth lateral wall elements. The thickness of the flow is 8 times the average particle diameter, in order to prevent border effects [2].
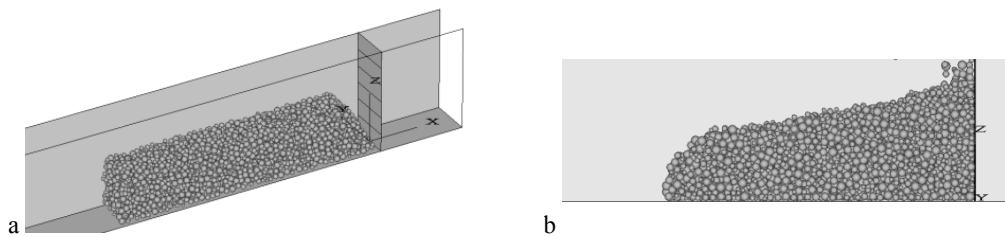

Fig. 1. DEM model, (a) 3D view of initial configuration and (b) lateral view of final deposit (reference impact, see Table 2).

Following the approach proposed by [3], the model features spherical particles whose rotation is inhibited for capturing the effect of the irregular shape of real soil particles. A linear contact model with Coulomb friction is adopted and contact parameters (see Table 2) are given typical values suitable for DEM models of soils [3]. No numerical damping is used in the simulations.

Table 1. Particle properties.

Average grain diameter, D (m)	0.3
Ratio between largest and smallest diameters	2.4
Particle unit weight, γ_s (kN/m³)	26
Contact stiffness (normal) k_n/D (MPa)	300
Contact stiffness (shear) k_s/D (MPa)	300
Contact friction coefficient	0.3

3. DEM simulations

The simulations consider the impact process only, while both triggering and the propagation phase of the flow are disregarded. For this reason, the impacting granular mass is generated just in front of the obstacle and horizontal uniform impact velocity is assigned to all particles. Vertical gravity force is applied at the same time. The initial conditions take into consideration a large variety of geometrical/mechanical factors, such as the initial front inclination, its height, the initial void ratio, the length of the impacting mass and the inter-particle friction angle (Table 1 and 2).

Table 2. Model data and test conditions (the values picked for the reference test are reported between brackets)

Length of the grain assembly, l (m)	2.5–80 (15)
Width of the grain assembly, b (m)	8 D
Height of the grain assembly, h (m)	1.5–7.5 (3)
Inclination of the front, α (°)	60–90 (60)
Initial porosity, por	0.45–0.65 (0.45)
Number of grains	700–33600 (4200)
Initial velocity u_0 (m/s)	4.0–52.4 (8.8)

4. Numerical results

In this section we show the main features of the impacts, and introduce the non-dimensional variables that are used to describe the *MIF*. The main outcomes of the parametric simulations are also illustrated and reported. The complete parametric study and the results of all simulations can be found in [1].
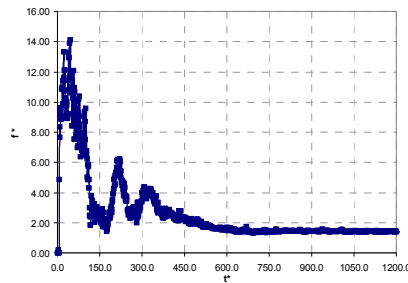

Fig. 2. Reference test: evolution of impact force with time.

The evolution of impact force with time for the reference test (Table 2) is shown in Figure 2. Results can be conveniently interpreted by introducing non-dimensional variables. f^* is a non-dimensional force, defined as:

$$f^* = \frac{f}{f_s}, \text{with } f_s = \frac{1}{2}\gamma_s h^2 b \tag{1}$$

where f is the impact force and f_s is the static force exerted by a fluid with unit weight equal to the unit weight of grains, γ_s. t^* is non-dimensional time, defined as:

$$t^* = \frac{t}{t_M}, \text{ with } t_M = \pi \left/ \sqrt{\frac{k_N}{m_g}} \right. \tag{2}$$

where t is time elapsed from the impact and t_M corresponds to the duration of the collision between two average grains. The Froude number F_r can also be introduced:

$$F_r = \frac{u_0}{\sqrt{gh}} \tag{3}$$

where u_0 is impact velocity and h is flow height.

The peak of the impact force is reached very rapidly and the residual force is about twice the static one (Fig. 2). Before the mass attains the residual state, at least two secondary impact waves are observed. The time interval between successive peaks is strictly associated with the velocity of wave propagation within the granular mass (*i.e.*, with stiffness and density of the equivalent deformable continuum), and is not dependent on impact velocity (Fig. 3a).
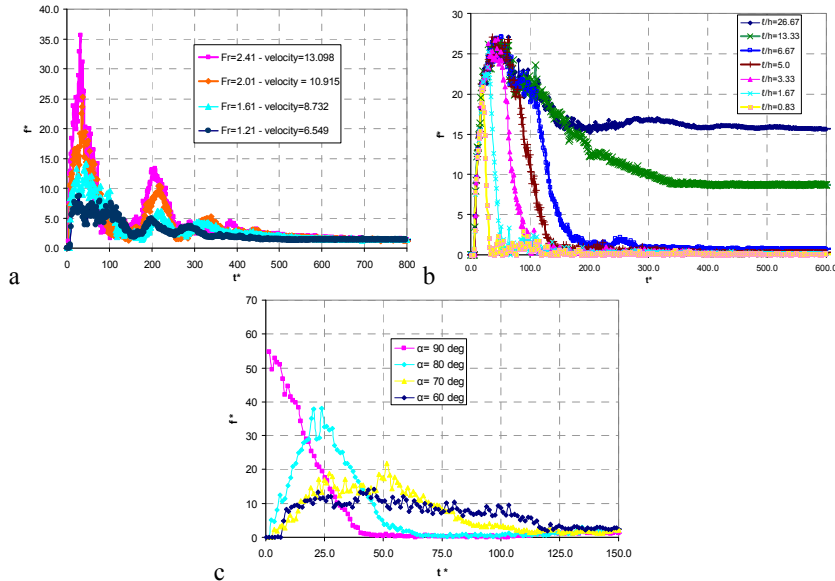

Fig. 3. Time evolution of non-dimensional impact force (*f** vs. *t**): influence of (a) impact velocity, (b) flow length and (c) front inclination.

Impact velocity has a clear influence on impact force (Fig. 3a). On the contrary, the length of the flowing mass (*i.e.*, the total mass) is almost irrelevant as far as the *MIF* is concerned; on the contrary it determines the duration of the impact and the residual force (Fig. 3b). *MIF* increases with front inclination, while the peak of the impact force is recorded after a time interval rapidly decreasing with the front inclination (Fig. 3c). Note that $\alpha = 90°$ is a limit condition, where all particles at the front of the flowing mass impact the barrier at the same instant of time.

5. Empirical equation

In order to interpret the results of the simulations is useful to highlight the dynamic nature of the impact by subtracting from the impact force the static value represented by the passive thrust, S_p, which corresponds to the value *MIF* tends to when impact velocity tends to zero. Two new variables are therefore introduced:

$$\Delta_{MIF} = MIF - S_P \text{ and } \Delta_{MIF*} = \Delta_{MIF} / f_s \tag{4}$$

The results of all simulations performed in the investigated range of parameters can be described by the formula:

$$\Delta_{MIF*} = a_1 F_{rM} F_r + a_2 F_r^2 \text{ with } F_{rM} = \frac{u_M}{\sqrt{gh}} \tag{5}$$

where a_1 and a_2 are two non-dimensional coefficients (Table 3) and F_{rM} is the intrinsic Froude number and depends on the propagation velocity of compression waves within the impacting mass (u_M, approximately equal to 200 m/s for the numerical model) and flow height.

Table 3. Interpolation parameters a_1 and a_2 as a function of front inclination and intrinsic Froude number.

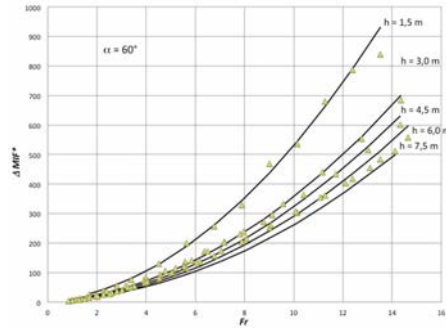| α (°)	a_1	a_2				
		$F_{rM} = 52$ (h=1.5 m)	$F_{rM} = 36.8$ (h=3.0 m)	$F_{rM} = 30$ (h=4.5 m)	$F_{rM} = 26$ (h=6.0 m)	$F_{rM} = 23.3$ (h=7.5 m)
60	.15	4.5	3.0	2.75	2.5	2.25
70	.4	3.5	2.75	2.5	2.25	2
80	.55	2.8	2.25	2	1.8	1.7
90	1.0	1.3	1.25	1.1	1.05	1.0

Fig. 4. Δ_{MIF^*} vs F_r, numerical data and interpolation (Eq. 5).

The accuracy of Eq. 5 is shown in Figure 4 for the case $\alpha = 60°$. The maximum average dynamic pressure exerted by the granular mass can then be written as:

$$\Delta p_{MAX} = \frac{\Delta_{MIF}}{bh} = a_1 \frac{1}{2} \rho_s u_M u_0 + a_2 \frac{1}{2} \rho_s u_0^2 \tag{6}$$

As widely discussed in [1], the first term of Eq. 6 is linear with u_0 and depends on the stiffness and density of the material. This term corresponds to the pressure exerted by the impact of a deformable body. The second term, is quadratic with u_0, and represents the dynamic pressure exerted by a fluid.

6. Comparison with literature data

In order to assess the reliability of the proposed formula, it is useful to compare it with experimental observations. Simple empirical hydrodynamic formulae have been extensively used in the literature to interpret the results of experiments or to back-analyse real scale events. In these formulae the dynamic pressure is typically evaluated as [4]:

$$p = \alpha \rho \, u_0^2 \tag{7}$$

where α is an empirical coefficient and ρ is the density of fluid. The empiric and purely descriptive nature of Eq. 7 is evident if we consider that values of α in the range between 0.45 and 11.0 are reported by several authors that studied a number of different cases, including real scale events and small scale experiments, as listed in Table 4. The same interpretation can be adopted for back-analysing in terms of empirical coefficient α the dynamic pressure predicted by Eq. 6 (which in turn is based on the DEM simulations), at least for the smaller front inclination, *i.e.* when the influence of the deformable body contribution is smaller (see Table 3).

Table 4. Empirical coefficient α.

Reference	α	Event
Scheidl et al. [5]	2.0-11.0	Small scale experiments
Zhang [6]	3.0-5.0	Jiangjia Ravine, China
Watanabe and Ikeya [7]	2.0	Nojiri Ravine, Japan
Hungr et al. [8]	1.5	British Columbia, Canada
Mizuyama [9]	1.0	Yakedake, Nigorisawa and Urakawa, Japan
Armanini [10]	0.45-2.2	Small scale experiments
This paper, [1]	3.0-12.0	DEM simulations (front inclination 60°)

Although it may appear quite reductive to interpret the numerical results and the derived formula (Eq. 6) by using a more simple empiric formula (where the term linear with u_0 is neglected), the comparison is quite interesting considering the large ad common use of the latter. In this regard, it is worth noting that the values of α corresponding to the application of Eq. 6 are well within the variation range determined from small scale and real scale flows.

7. Concluding remarks

Common design approaches for sheltering structures against impacts of dry granular flows are based on pseudo-static methods and empirical formulae that are based on analogies with hydrostatic conditions, or assume hydrodynamic or deformable body models for the impact. The results presented here demonstrate that these approaches are oversimplified, and in particular that it is impossible to assess the maximum impact force by employing a unique interpreting model for any value of impact velocity and front inclination. The new formula proposed for the maximum impact force combines those that one would obtain with the deformable body and fluid models. Note that the importance of the two mentioned components depends on a number of factors: some of them are geometrical, others are associated with the mechanical behavior and properties of the impacting material.

Acknowledgements

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