



The effect of the front inclination on the impact forces transmitted by granular flows to rigid structures

Francesca Ceccato, Paolo Simonini, Claudio di Prisco, Irene Redaelli

Abstract

The assessment of the damage of existing structures caused by flow landslides, as well as the design of sheltering structures, requires the evaluation of the forces arising during the impact. In particular, the peak force depends on several factors such as the impact velocity, the material bulk density, the flow thickness, and the material compressibility. The effect of the front shape on the force evolution has been rarely taken into account because it is experimentally very difficult to consider. The aim of this paper is to study numerically the impact process evaluating the effect of the material constitutive parameters and shape of the flow front. Large deformations of the granular material are simulated by employing a 3D numerical approach based on the Material Point Method (MPM). The granular material mechanical behavior is simulated by means of an elastic perfectly plastic model with a Mohr-Coulomb failure criterion. The soil mass is initially positioned in front of the wall with a prescribed uniform velocity and the evolution of the impact force is monitored. The results show that the front shape not only influences the peak pressure, but also the evolution of the impact force with time.

Keywords

Impact forces, granular flows, MPM, front inclination, landslide-structure interaction.

Introduction

The assessment of the damage caused by either granular flows or snow avalanches to existing structures, as well as the design of sheltering structures, requires the evaluation of impact forces. Several empirically based relationships have been proposed to calculate the peak force. It is known that the force is a function of the impact velocity (v_0), the bulk density (ρ) of the material and the flow thickness (h), but also other factors may be important.

Most of these relationships are derived by considering the granular material like an incompressible fluid and are based on either the hydrostatic or on the hydrodynamic approach. The first assumes a triangular distribution of the normal pressure, whose maximum value is a function of both the hydrostatic pressure (ρgh) and an empirical factor (k) [5, 25]. The latter assumes a constant pressure distribution along depth in which the pressure is a parabolic function of the mass velocity (ρv_0^2) and depends on an empirical factor (a) [7, 29]. The empirical factors a and k are a function of the flow characteristics and they vary in a wide range, making the

practical use of these approaches rather difficult. In fact, the expression of the hydrodynamic pressure holds true in a steady case where the flow is deflected at an angle of 90° , but not during the first milliseconds of a vigorous impact.

As soon as the flow hits the wall, the material next to the obstacle is stopped abruptly, and a compression shock wave travels upstream with a celerity c , causing the material to decelerate [17]. Applying the principle of linear impulse, the dynamic peak pressure results

$$p = \rho c v_0 \quad (1)$$

where c is close to the sound speed, depending on both the elastic modulus (E) and the material density:

$$c = \sqrt{E/\rho} \quad (2)$$

This parameter is difficult to determine accurately and, to the author knowledge, no experimental measurements have been never performed.

Mixed approaches, in which the peak pressure is a function of both velocity and thickness, have also been proposed [4, 13].

Besides the hydro-related models, even approaches introduced for rock boulder impacts are largely employed [11, 12]. Most of these models are based on the

Hertz model, assuming the material mechanical behavior to be elastic. The impact force according to these approaches is related to the properties of the grains (diameter, elastic modulus), of the flow (solid concentration, velocity) and of the grain-structure interaction (type of contact).

In general, we can state that numerous factors besides v_0 , ρ and h affect the impact force value, such as the material compressibility [18], the formation of a stagnant zone upstream of the obstacle [16] and so on. Considerable effort has been already spent in the study of the impact process, but the phenomenon has not been fully highlighted yet.

The effect of the front shape on the force evolution has rarely been taken into account, because it is experimentally very difficult to be considered. To the authors knowledge, only in [8], by discussing numerical results derived applying the discrete element method (DEM), this aspect has been critically considered. The aim of this paper is to study numerically the impact process, by evaluating in details the role of the shape of the flow front.

When a granular mass flows along a natural slope, the inclination of the front is related to numerous factors such as the slope inclination, the coefficient of lateral soil mass spreading, the average velocity of the sliding mass, the overall friction angle and the density of the soil mass [14, 19, 24]. Analogously to what done in [8], here these aspects are not investigated, since the propagation phase is disregarded and the mass is placed in front of the obstacle with an initial uniform velocity.

Large deformations of the granular material are simulated by employing a 3D numerical approach based on the Material Point Method (MPM). The MPM is a continuum-based meshless method specifically developed for large deformations of history dependent materials. This numerical approach simulates large displacements by means of Lagrangian points moving through an Eulerian grid [27]. This method has been successfully applied to the study of a large number of geomechanical problems such as landslides and snow

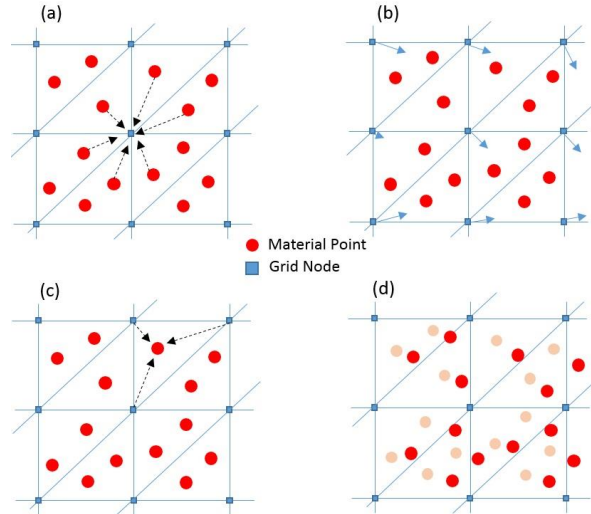


Figure 1 Computational scheme of MPM

Table 1 Material reference parameters

Young modulus [kPa]	E	58000
Poisson's ratio [-]	ν	0.2
Porosity [-]	n	0.45
Bulk density [kg/m ³]	ρ	1475
Friction angle [°]	ϕ	33
Speed of sound [m/s]	c	200

avalanches [21, 26, 28], slope stability [1, 2], and soil penetration problems [9, 23].

The debate around the most appropriate constitutive equation for describing soil flows is still animated [3, 15]. Part of the scientific community uses soil-mechanics concepts (elastoplasticity) [15, 20], while another part prefers viscoplastic models [10, 22], and others provide phenomenological constitutive equations merging solid and fluid mechanics concepts [6]. In this paper, we use an elastic-perfectly plastic model with a Mohr-Coulomb failure criterion.

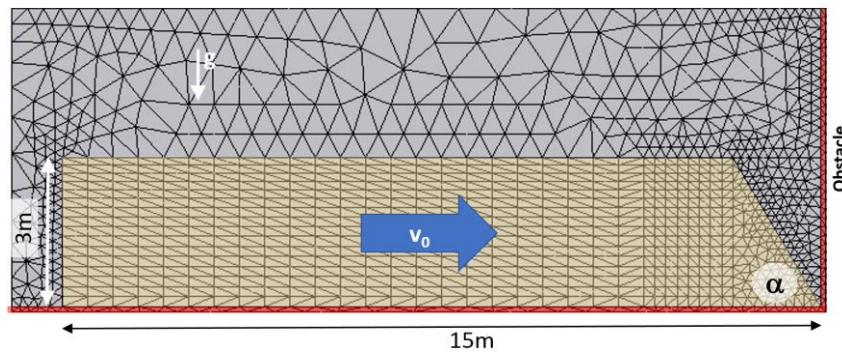


Figure 2 Geometry and spatial discretization

The numerical model

The numerical simulations are performed by using the dynamic explicit code Anura3D (www.anura3d.eu). In MPM, the continuum body is discretized by means of a set of Lagrangian points, called material points (MPs). They carry all the information of the continuum such as density, velocity, acceleration, stress, strain, material parameters as well as external loads. The MPs do not represent single soil grains, like in DEM, but a portion of the continuum volume.

Large deformations are simulated by MPs moving through a fix computational finite element mesh which covers the entire spatial region into which the solid is expected to move. This grid is used to solve the system of equilibrium equations, but it does not deform with the body like in Lagrangian Finite Element Method.

At the beginning of each time increment, the information is mapped from the MPs to the computational nodes of the mesh by means of shape functions (Fig. 1a). The governing equations of motion are solved (Fig. 1b) and the nodal values are used to compute strains and stresses at the MPs (Fig. 1c). Finally, the position of MPs is updated and a new element is associated with those MPs that crossed element boundaries (Fig. 1d).

Geometry and discretization of the model are shown in Fig. 2. The flowing mass is initially placed in front of the obstacle with a uniform velocity $v_o=4, 8.8, 16, 32, 40$, or 52m/s . The flow is 3.0m thick and 15.0m long. The model is 0.2m wide. The numerical results are normalized with respect to the model width. The considered inclinations of the front (α) are $60^\circ, 70^\circ, 80^\circ$ and 90° . The obstacle is 6m -high and all the boundaries are assumed to be smooth.

The mesh is refined in the proximity of the obstacle. 20 MPs are initially placed inside each active element (yellow color in Fig. 2).

The behaviour of the soil is modelled with elastic-perfectly-plastic model with Mohr-Coulomb failure criterion. The reference parameters are summarized in Tab. 1. Different values of both the Young modulus and the friction angle will be also considered in the following.

Results

Let us consider a vertical front, i.e. $\alpha=90^\circ$. When the granular flow hits the obstacle, it is forced to be compressed and the mean effective stress increases significantly (compression shock, see. Fig. 3). The stress behind this shock determines the force on the obstacle at the instant of the impact.

The compression shock wave propagates upstream causing a progressive deceleration of the flow. This

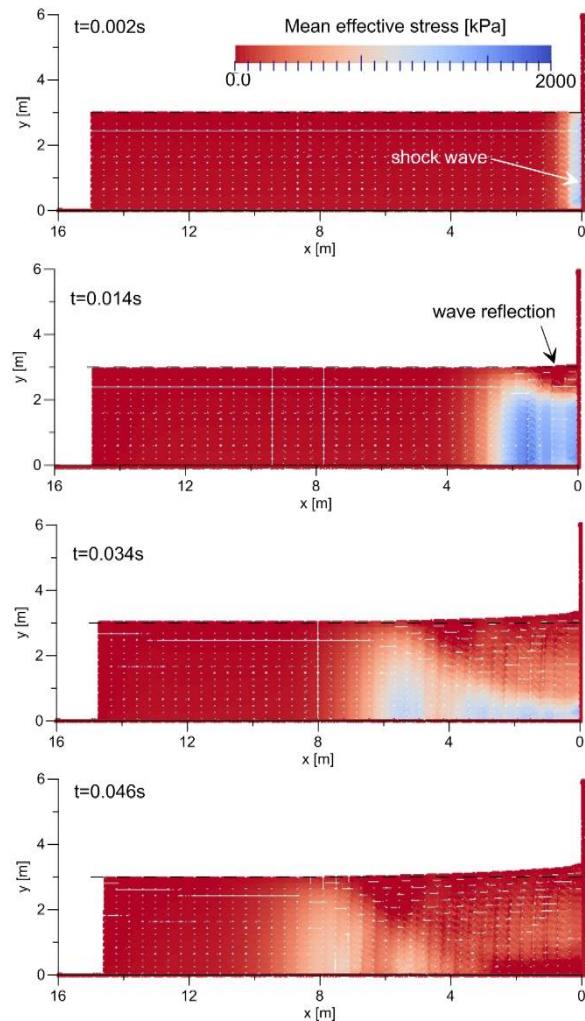


Figure 3 Mean effective stress contour at different time ($\alpha=90^\circ, v_o=8.8\text{m/s}$)

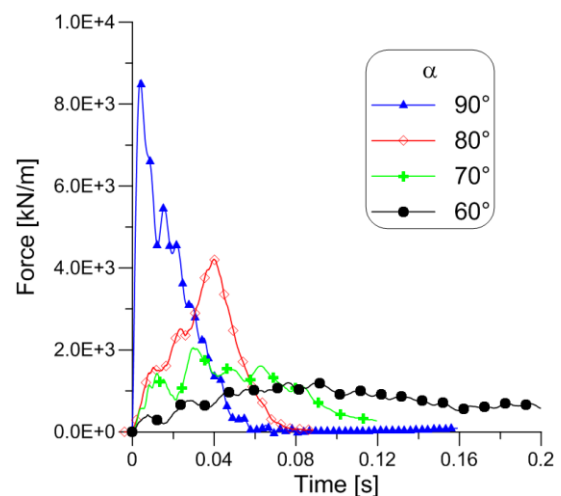


Figure 4 Impact force evolution with time for different front inclinations ($v_o=8.8\text{m/s}$)

phenomenon is the well-known in hydraulics water hammer phenomenon. In case of confined flow, i.e. absence of open boundaries, this high pressure remains constant for a relatively long time. In contrast, in a free-surface granular flow, the lack of confinement causes vertically directed rarefaction wave, causing a progressive decrease in the mean effective stress (Fig. 3). This is why the time interval during which the obstacle feels the large pressure is usually very short (a fraction of a second) (Fig. 4).

The generation of the shock wave and its spatial propagation is clearly visualized in Fig. 3 for the simplified case of a rectangular flow. For non-vertical fronts, the process is more complex because the shape of the flow's boundaries changes with time during the impact.

The peak force depends not only on the pressure, but also on the height of the flow in contact with the obstacle, which increases with time. Decreasing the front inclination, the peak force decreases and the time at which it occurs (peak time) increases (Fig. 4).

It is observed that the height of the material in contact with the obstacle at the peak time (h_{peak}) is lower than the reference flow height (h) (Fig. 5). However, given the difficulty of evaluating h_{peak} in practical cases, in the following the authors will refer to the reference height h .

In general, and accordingly to what proposed by [8], the peak force (F) can be decomposed in the sum of a dynamic contribution (F_d) and a static contribution (F_s). The latter is assumed to be equal to the passive earth thrust

$$F_s = \frac{1}{2} \rho k_p h^2 \quad (3)$$

where k_p is the passive earth pressure coefficient, which is a function of the friction angle and can be estimated as

$$k_p = \tan^2(45 + \varphi/2) \quad (4)$$

In the range of velocities considered in this study, F_s is small compared with F_d .

Fig. 6 shows the dynamic component of the peak force as a function of the impact velocity for different flow inclinations. It can be observed that the relationship is linear only for $\alpha=90^\circ$. Moreover, in this case, the values match very well the force values obtained by the linear-impulse theory, i.e. assuming a maximum pressure computed with Eq. 1, constant with depth (dashed line in Fig. 6).

The MPM peak forces are also in good agreement with the results obtained with DEM simulations by [8], where the same geometry and impact velocity are applied and a similar celerity of the compression wave is estimated (Fig. 7).

The celerity of the compression wave in the granular flow, here approximated with the sound speed, is a key parameter in the evolution of the impact force. Fig. 8

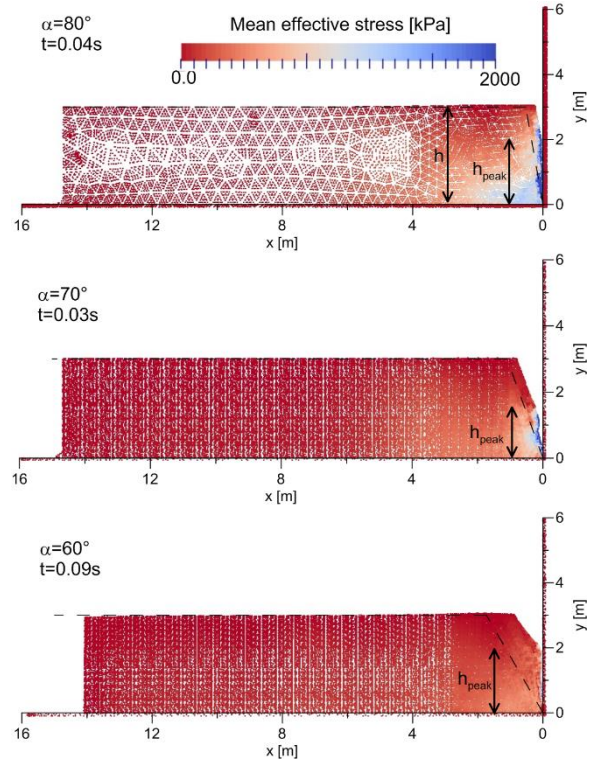


Figure 5 Mean effective stress at the peak time for different front inclinations.

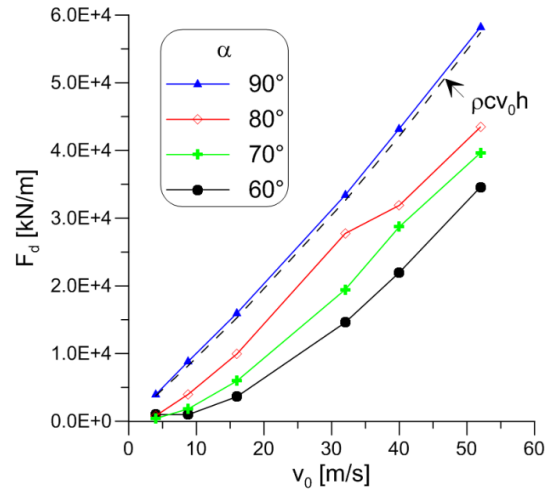


Figure 6 Dynamic force with impact velocity for different inclinations of the front

shows the impact force with time for different values of Young's modulus in case $\alpha=90^\circ$ and $v_0=8.8\text{m/s}$. Decreasing the Young's modulus, the peak force decreases because the sound speed decreases (see Eq. 2). When $v_0 > c$ the force increases monotonically and no peak is observed.

The celerity of the compression wave in a granular flow is very difficult to estimate due to the discrete

nature of the material. In granular flows, the material can be in a collisional state, i.e. the grains are not permanently in contact and force chains do not develop. This makes the definition of the elastic modulus particularly difficult and questionable.

The friction angle of the material seems, in contrast, not to play a significant role on the peak force. Nevertheless, both the dynamic and the static components of the force increase with ϕ (Fig. 9).

Conclusions

In this paper, the force developing at the impact of a granular flow on a rigid obstacle is numerically tackled. In particular, the influence of the front inclination in affecting the maximum impact force is analyzed.

The MPM numerical code Anura3D has been employed; the soil mass mechanical behavior has been simulated by using an elastic perfectly plastic constitutive relationship.

The authors observe that:

- (i) when the soil mass front is parallel to the wall, the dynamic peak force is well captured by the theory of linear impulse;
- (ii) The force increases linearly with the velocity and not quadratically as predicted by hydrodynamic approaches;
- (iii) Decreasing the front inclination, the peak force decreases and the linear dependence with the velocity is lost.

This agrees with the observation derived by [8], which studied the impact process applying a discrete element method. For the considered dense granular flow, despite the completely different approach, the results obtained by employing the MPM are in good agreement with those obtained by means of DEM.

From a quantitative point of view, the study showed that the celerity of the compression wave is a key parameter to evaluate the impact force. The comparison between DEM and MPM numerical results has been done by imposing the same value of celerity.

Nevertheless, it is very difficult to determine in a granular flow such a parameter. Future experimental and numerical studies should address this aspect.

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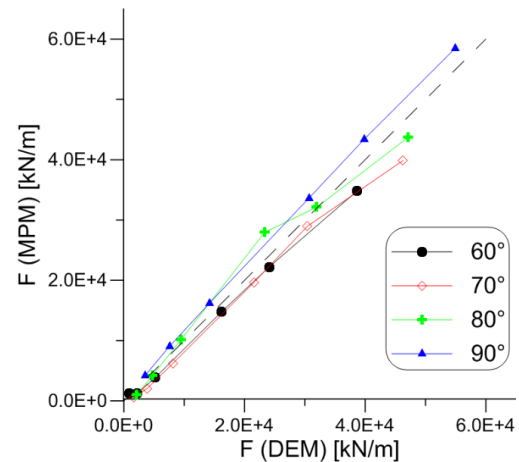


Figure 7 Comparisons between MPM simulations and DEM simulations by [8].

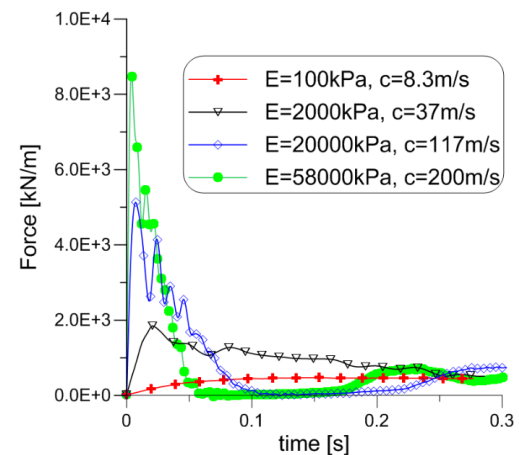


Figure 8 Force evolution for different values of the Young modulus ($v_0=8.8\text{m/s}$, $\alpha=90^\circ$)

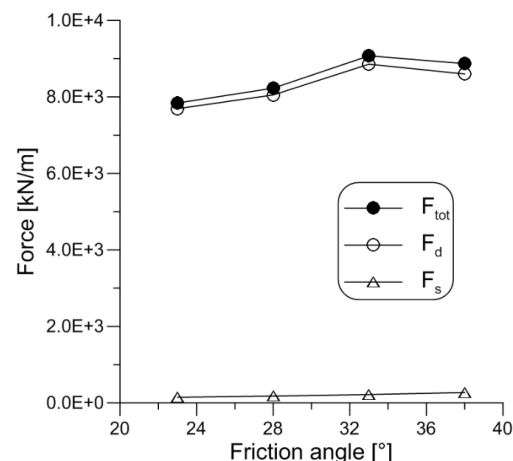


Figure 9 Effect of friction angle on impact force ($v_0=8.8\text{m/s}$, $\alpha=90^\circ$)

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Francesca Ceccato 

University of Padova, via Ognissanti 39, 35129 Padova, Italy
E-mail: francesca.ceccato@dicea.unipd.it

Paolo Simonini

University of Padova, via Ognissanti 39, 35129 Padova, Italy

Claudio di Prisco

Politecnico di Milano, Pz. L. da Vinci 32, 20133 Milano, Italy

Irene Redaelli

Politecnico di Milano, Pz. L. da Vinci 32, 20133 Milano, Italy