DYNAMIC IMPACT OF DEBRIS AVALANCHES ON STRUCTURES

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Abstract

Flow-like landslides are largely studied because they cause damage to the structures and loss of life. In particular, debris avalanches propagate quickly along slopes for hundred meters. This work deals with the dynamic impact of debris avalanches against civil structures. The analyses are carried out through a numerical code implementing the Smoothed Particle Hydrodynamic (SPH) method that has reasonable computational time for the accurate evaluation of kinematical features of the debris avalanches such as heights, velocities and pore water pressures during the propagation stage. The dynamic impact is evaluated for different scenarios of landslides differently triggered inside the source areas. Distinct literature formulations are used to evaluate the impact pressure and its time variation. The numerical results outline the ranges of potential impact pressures on civil structures the threatened to be impacted by a debris avalanche. A comparison is also made with critical values of impact pressures recorded in a similar context, and it is outlined the potential damage from such impact scenarios for the existing structures.

Keywords: SPH, structures, landslide, dynamic impact, flow.
1 INTRODUCTION

Flow-like landslides includes several natural phenomena which propagate along the slopes (debris avalanches) or drainage line (debris flows). They are extremely rapid and travel for hundreds of meters with increase of volume during the propagation stage [1]. The attention is here focused on the debris avalanches defined by [2] as “very rapid to extremely rapid shallow flow of partially or fully saturated debris on a steep slope, without confinement in an established channel”. Several methods have been used to analyze the propagation of flow-like landslides, e.g. Finite Element Method [3], Finite Difference Method [4], Material Point Method [5]. The “GeoFlow SPH” model (SPH) is used in this paper as it is considered capable to provide a good compromise of accuracy and time efficiency [6-7]. The area of Cervinara (Southern Italy) is selected as case study inside the wider context of the pyroclastic soils originated from the explosive eruptions of the Vesuvius volcano. The slopes facing the municipality of Cervinara are very steep, 35 degrees on average, and are covered by pyroclastic deposits 2-3 m thick [8]. In December 1999 a number of shallow landslides were triggered due to heavy rainfall and propagated as flows. Among these, a debris avalanche turned into a channelized flow and caused 5 victims [9]. Other soil volumes could be potentially triggered and the landslides could reach the piedmont area where several civil structures exist.

The paper proposes some preliminary numerical analyses to outline the ranges of velocity ($v$) and height ($h$) of the debris avalanches potentially occurring at specific points of the study area (Fig. 1). Then, the mean impact pressure ($p$) values are computed by using distinct formulations available in the literature.

![Figure 1: Schematic of the mean impact pressure ($p$) of a flow characterized by a velocity ($v$) and a height ($h$).](image)

2 METHODS

The “GeoFlow_SPH” model proposed by [6] is here used to simulate the propagation pattern of a number of selected debris avalanches. This model is a depth-integrated hydro-mechanical coupled model that schematizes the propagating mass into a mixture of solid skeleton and pore water. It is based on a set of partial differential equations such as: i) the balance of mass of the mixture combined with the balance off the linear momentum of the pore water pressure; ii) the balance of the linear momentum of the mixture; iii) the rheological equation of the mixture; iv) the kinematical relations between velocity and deformation. The Smoothed Particle Hydrodynamics (SPH) numerical technique is particularly useful to ensure appropriate accuracy and reasonable computational times. More details are provided in [6-10] and [7]. The input data of the model are: the Digital Terrain Model (DTM) where the potential debris avalanches may propagate; the rheological features of the flows, here taken from [8]. Particularly, $h_{trig}$ is the soil thickness in the triggering area; $\tan \varphi_b$ is the base friction angle of the
flow propagating over the ground surface; $h_{wrel}$ is the height of the water table relative to the soil thickness in the triggering area; $p_{wrel}$ is the base pore water pressure divided by the soil liquefaction value; $c_v$ is the soil consolidation coefficient; and $E_r$ is the bed entrainment coefficient regulating the increase of landslide volume. Two set of rheological properties are referred, as taken from successful back-analyses of real debris avalanches occurred at locations not far from the study area, namely Monte Albino (“A” in Tab.1), and Monte Foresta (“F” in Tab. 1).

Several potential triggering volumes are considered to propagate over the DTM (Fig. 2b). The peak impact force is calculated in correspondence of buildings (points B1, B2, B3, Fig. 2a) and streets (points S1, S2, Fig. 2a) starting from the height-velocity ($h$-$v$) pairs of the flow and using literature formulations.

<table>
<thead>
<tr>
<th>Rheology</th>
<th>$\phi^*$</th>
<th>$\tan \phi^*$</th>
<th>$h_{wrel}$</th>
<th>$p_{wrel}$</th>
<th>$c_v$</th>
<th>$E_r$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>19°</td>
<td>0.34</td>
<td>0.4</td>
<td>1.0</td>
<td>0.01</td>
<td>0.019</td>
<td>Cuomo et al. (2014)</td>
</tr>
<tr>
<td>F</td>
<td>22°</td>
<td>0.40</td>
<td>0.4</td>
<td>1.0</td>
<td>0.01</td>
<td>0.007</td>
<td>Cuomo et al. (2016)</td>
</tr>
</tbody>
</table>

Table 1. Sets of rheological properties used in the numerical modelling.

The pressure induced by lateral forces could be very dangerous for structures as showed by [11]. Here, the pressure is considered applied on the structures as constant along the height as a simplification of real distribution during a natural phenomenon (Fig. 1). [12] proposed two formulations that depend on the impact mechanism: i) formation of a completely reflected wave; ii) formation of a vertical bulge; the last formulation depends on both height and velocity and is here considered (Eq. 3 in Tab. 2). [13] carried out real scale tests and laboratory tests to evaluate the impact pressure against rigid barriers and they evaluated the impact introducing an empirical coefficient $k$ comprises between 1.5 and 5 (Eqs. 1 and 2, respectively in Tab. 2). Finally, [14] evaluate the impact force as the sum of a static component (height dependent) and a dynamic component (velocity dependent), (Eq. 4). The peak values of pressure versus height are compared with the maximum pressures applied to the structures as function of reinforced; the maximum pressure applied to the structures are taken by [11]. In particular, three reinforce level are considered taking into account a reinforced-concrete column: i)
strongly-reinforced; ii) medium-reinforced; iii) low-reinforced. It is possible to calculate the critical pressure that gives the ultimate bending moment inside the structures as function of flow height.

Table 2. Empirical equations used for estimation of impact pressure of the debris avalanche against structures.

<table>
<thead>
<tr>
<th>Name</th>
<th>Equation</th>
<th>Notes</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eq. 1</td>
<td>( p = k \rho_m v^2 )</td>
<td>( k=1.5 )</td>
<td>Canelli et al. (2012)</td>
</tr>
<tr>
<td>Eq. 2</td>
<td>( p = k \rho_m v^2 )</td>
<td>( k=5 )</td>
<td>Canelli et al. (2012)</td>
</tr>
<tr>
<td>Eq. 3</td>
<td>( p = (0.5g \rho_m h^2 + \alpha h v^2 \rho_m)/A )</td>
<td>( \alpha=1 )</td>
<td>Armanini et al. (2011)</td>
</tr>
<tr>
<td>Eq. 4</td>
<td>( p = 0.5Kp \rho_m gh + 5v^2 \rho_m )</td>
<td>( Kp=\tan^2(\pi/4+\phi/2) )</td>
<td>Gioffrè et al. (2017)</td>
</tr>
</tbody>
</table>

3 RESULTS AND DISCUSSION

The flow deposition heights are showed in Fig. 3 for both rheology A (Case A20) and rheology F (Case F20). The debris avalanches reach the structures in both cases and they are characterized by a maximum height equal to 1.5 m at the distal part of the flow deposit. The debris avalanche results in greater deposition height for the rheology “A” than for rheology “F” and the affected area is larger for the rheology “A” than rheology “F”.

In Fig. 4 the heights and velocities computed in the control points are showed versus time. In correspondence of the structures (points B1 and B2) the flow deposits in both cases; while, the flow does not deposit in correspondence of the streets and the structure at point B3 where the flow height decreases until zero during the propagation stage.

The highest flow deposition height is equal to 6 m and is recorded for rheology A and in correspondence of point B2. The velocities increase quickly until a peak and then decreases down to zero in about 5 seconds. The maximum velocity is recorded in correspondence of the control point B3 for both rheologies (A and F) with the peak value is respectively equal to 16 m/s and 12 m/s. In correspondence of the street, the maximum height is simulated for rheology A and is equal to 3 m while the velocity is the lowest among all the control points and is equal to 1 m/s. The impact pressures are computed versus time considering different control points and rheologies in correspondence of the buildings (Fig. 5).
Figure 4: Heights ($h$) and velocity ($v$) versus time for a) rheology A and b) rheology F.

Figure 5: Maximum pressure ($p$) of the flow versus time in correspondence of the buildings (B1 and B2) for flow rheology A (Case A20, Fig. 5a, c) and rheology F (Case F20, Fig. 5b, d).

The impact pressure increases until a peak value (with the peak time at about 20 s) and then decreases. In general, the dynamic impulse of the pressure has duration less than 10 seconds in all the cases. The pressure decreases down to a constant value calculated through Eqs. 3-4, which are both dependent on height and velocity of the debris avalanche. The impact pressures are comparable for the Case A20 and Case F20. In particular, the maximum peak value is given by Eq. 4 and equal to 900 kPa and 2,000 kPa, respectively in correspondence of the points B2 and B3 (Fig. 6a) for case A20 and equal to 1,000 kPa in correspondence of the same point for case F20. The pressure calculated through the Eqs. 1 and 2 is comparable to the pressure calculated from Eq. 4 considering the maximum value of empirical coefficient $k$ (equal to 5); at the same time, pressure computed through Eq. 1-2 are in agreement with the
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The critical pressure calculated through Eq. 3 considering the minimum value of $k$ (equal to 1.5). The control point B3 has the highest value of pressure independent of the equation used for computing the pressure impact.

The case A20 presents the highest values of impact pressure in correspondence of the control point B3 (equal to 2,000 kPa) while the maximum impact pressures are comparable between the two rheologies considering the control points B1 and B2.

![Figure 6: Peak pressure estimated in the different control points (B1, B2, and B3) for: a) flow rheology A; b) flow rheology F.](image)

In Fig. 7, the pressure calculated through literature formulae is showed as function of the impact height and compared with the critical pressure of three levels of reinforced column reported in [11]. It is not possible to identify a critical value of impact pressure, but it is possible to individuate the trend of pressure as function of the impact height. In the case A20 (Fig. 7a), the pressures caused by the debris avalanches are lower than the critical pressure of the strongly-reinforced column for impact height less than 1 m; the medium-reinforced column and low-reinforced column can resist to the impact for values of impact height less than 0.8 m. The impact pressure increases when the impact height increase, then the structures should be not enough resistant for impact height more than 1 m. The strongly-reinforced column resists in correspondence of all control points considering the case F20 (Fig. 7b).

![Figure 7: Black lines indicate the critical pressure computed for differently reinforced structures as a function the impact height ($H$) of a debris avalanche. Coloured lines indicated the flow pressure computed through different formulations (Eqs. 1–4) with reference to different control points such as B1 (dashed line), B2 (dots line), B3 (dashed dot line).](image)
4 CONCLUSION

The paper deals with the dynamic phenomena of debris avalanche against structures during the propagation. Two different rheologies are taken into account and the area affected by different debris avalanches is studied; it is shown that the debris avalanches propagate until the urban zone. Then, the pairs of height-velocity are computed in several control points in correspondence of either building (B points) or streets (S points). During the propagation, the flow may produce two different scenarios: i) the height increases until a maximum value and then decreases until a constant value (there is a deposition of material); ii) the height increases until a maximum value and then decreases until a null value; while, the flow-velocities increases until a peak value and then decreases until null value. The impact pressure exerted against the structures is calculated considering distinct literature formulae and starting by the pairs height-velocity previously computed. The pressure versus time increases until the peak value and then decreases following two different trends: i) the flow impacted against the structures and a part of it deposited; in this case the deposition of material exerted a force also after the end of the propagation; ii) the flow propagate without deposition of material in the surrounding of the structure so that the force is null after the propagation of the flow. Finally, the range of maximum pressure are showed for each control point to give some indications to designer on the peak impact pressure due to an event such as a debris flow and take into account the several precautions for the aim taking into account that the peak pressure will be applied for several seconds.

A single critical value of flow pressure against the structure cannot be individuated because the critical pressure is dependent on the impact height. The pressures are plotted versus impact height and compared with the pressure that gives the ultimate bending moment taken by literature in relation to the impact height. The structures taken into account are able to resist to the debris avalanches for impact height less than 1 m in rheology A; while in rheology F, the strongly reinforced column is able to resist in all control points.

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REFERENCES


