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Numerical study of debris flows in presence of obstacles and retaining structures: A case study in the Italian Alps

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Abstract

Debris flows are one of the most frequent mass movement processes and occur in all regions with steep relief and at least occasional rainfall. Their high flow velocity, impact forces, and long runout, combined with poor temporal predictability, cause debris flows to be one of the most hazardous landslide types. An essential aspect of debris-flow risk management is the design of mitigation measures, which reduce the existing risk to an accepted level of residual risk, by reducing the potential damage that the moving mass can produce in terms of loss of human life and destruction of structures and infrastructures. Among these mitigation measures, transverse retention structures are used to delimit storage basins and prevent dangerous debris flows from reaching high-consequence areas. Due to the enormous impact forces that debris flows can exert on obstacles in their path, a reasonable planning requires that dynamic stresses are taken into account during the structural designing process, regardless of the complete (solid body barrier) or partial (open barrier) retention function that the type of selected structure can exert on the flowing mass. Since the village of Cancia, close to Cortina d'Ampezzo (Italian Dolomites), is hit by destructive debris flows for a long time, a storage basin delimited by natural and gabion barriers was built in 2000. In 2009 a severe event caused the partial collapse of the gabions and the overflow of the flowing mass. The present paper analyses through numerical modelling the dynamics of the flow and the influence of an abandoned building, existing inside the storage basin, on the occurred event.

Keywords: Debris flow; Retention barriers; Numerical modelling; Risk mitigation

1. Introduction

Debris flows are fast-flowing mass movements composed of a mixture of water, mud and debris, discharging through steep and confined channels (Iverson, 1997). This natural process represents a widespread threat to villages and infrastructures in mountain areas. Therefore, countermeasures have to be adopted by the local governments to mitigate the risk related to these phenomena.

In order to protect elements at risk and to reduce expected losses, different passive (e.g. land-use management, hazard delimitation) as well as active (e.g. structural measurement, protection forest) mitigation strategies are available (Holub and Fuchs, 2008). In particular active structural measures, such as retention basins, check dams and channelization are established in the management of mountain hazards. But, knowledge of debris-flow dynamics, impact forces and loads is needed to design these engineered structures strong enough to withstand the forces of the impacting mass.

A contribution to this knowledge can to a certain extent be obtained through numerical modelling (e.g., Iverson and Denlinger 2001; Pitman and Le 2005; Pudasaini et al. 2005; Pirulli 2005), if measures and observations for the model validation and calibration are available. Data from real events would allow one to completely bypass any possible scale effects affecting laboratory-scale results, but available data are usually limited.

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In the present paper, the numerical code RASH^{3D} (Pirulli, 2005) has been used to back-analyse the debris-flow event that affected the village of Cancia (Italian Dolomites) in July 2009.

Since destructive debris flows have long impacted this area, a storage basin delimited by a compacted soil embankment surrounded by gabions was built in 2000 as temporary mitigation structure. This barrier was partially destroyed by the July 18th, 2009 event. The collapse allowed the flowing mass to impact a house located downstream of the retention structure, where two people died.

Numerical modelling carried out with RASH^{3D} was aimed to investigate the dynamics of the flow and the influence on the event on an abandoned building located inside the storage basin.

2. Study area

The investigated area is the sector of the Boite river valley that is located at the foot of the Antelao Mountain, where the Cancia hamlet is (Fig. 1a). This hamlet is part of the Borca di Cadore municipality, which is located a few kilometers from Cortina d'Ampezzo (North-Eastern Italian Alps).

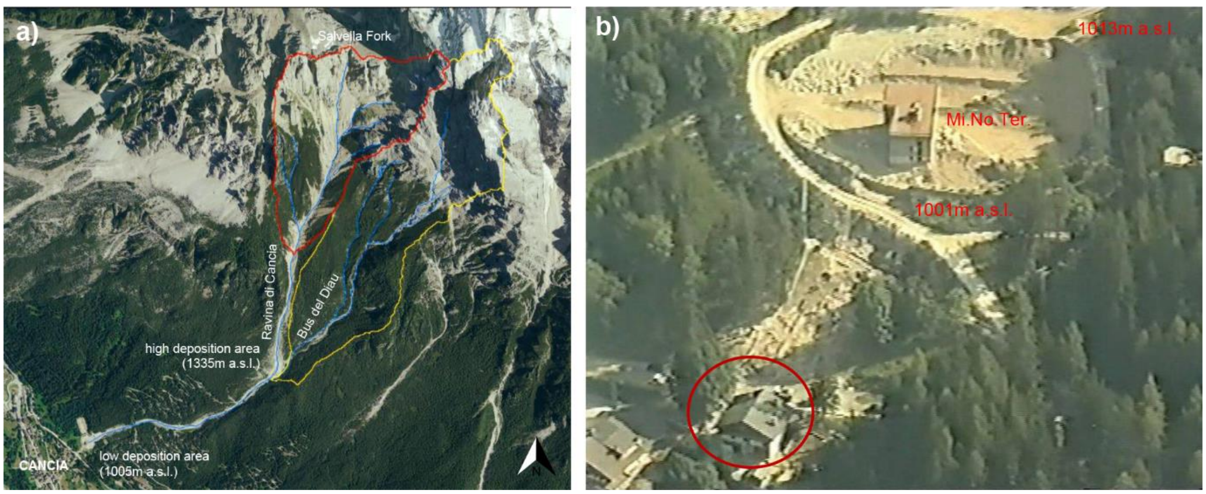

Fig. 1. (a) The Cancia study area (modified after Boreggio 2014); (b) the low deposition area where the partially destroyed storage basin is located. The red circle indicates the house impacted by the July 18th 2009 debris flow (image modified after Boreggio, 2014).

From a geological and structural point of view, the Antelao mountain range is between two important south-verging thrust faults: the Antelao line to the North and the Pieve di Cadore line to the South. The segmentation of the regional structure is further enhanced by movements along the faults and some existing paleotectonic fractures with NW-SE and NNW-SSW orientation. Cataclastic processes due to the above dislocations have originated the thick debris layer that characterizes the area (Turconi and Tuberga, 2010).

From a geomorphological point of view, the western side of the Antelao mountains presents an extremely irregular profile, because of the existing geological structure but also due to the intense modifications that occurred during the Würm glaciation. The retreat of glaciers made numerous mountainsides unstable and prone to collapse (Turconi and Tuberga, 2010).

Over the last few decades, the Antelao slope overhanging the Cancia hamlet has been object of periodic and intense instability phenomena in the form of debris flows.

The source area of these events extends from 1005 m a.s.l. at the terminus to 3264 m a.s.l. (Antelao Mountain), comprising a drainage area of about 1.8 km^2. Its main channel, namely Ravina di Cancia, has a length of about 2400m with a mean slope of about 20°. It originates at the feet of the Salvella Fork (2500 m a.s.l.) and ends at 1005m a.s.l in a storage basin (low deposition area), which was built in 2000 to protect the Cancia village. At the confluence with the Bus del Diau torrent (1335 m a.s.l.), the Ravina di Cancia pattern intersects a flat area (high deposition area) that was specifically built to divert and slow down flow events (Manassero et al., 2018).

The debris flow occurred on July 18th, 2009 was triggered by heavy but not exceptional rainfall; nevertheless, it was the most catastrophic of the historically occurred events, causing the loss of two human lives. The event, which triggered from the upper part of the Ravina di Cancia channel and the Bus del Diau (Fig. 1a), mobilized about 30.000 m^3 of material. This volume estimation is based on on-site surveys and comparison between pre- and post- event digital topography data and is defined as a function of the material eroded and deposited from the high deposition area up to the low deposition area and the Cancia hamlet (Fig. 1a).

During its propagation, it impacted and caused the partial collapse of some gabion barriers located upstream (1013m a.s.l.) and at the end (1001m a.s.l.) of the above mentioned storage basin (Fig. 1b). The partial collapse of the 1001m a.s.l. gabions allowed the mass to continue its running downstream and impact against a house located along its main flow trajectory, where two people were killed by the flowing mass (Fig. 1b).

The flowing mass entered the impacted house through windows and doors facing upstream and splashed up to the ceiling of the rooms. Immediately after, the mass fell through the floor into the downstairs garage and then exited the house from openings and pointed downstream.

After the event it was observed that gabions were not joined together, thus preventing the structure to act as a monolithic mass against the flow. Furthermore, a large quantity of fine size aggregates filled the inner part of the gabions, thus preventing the water to flow through the wall and not minimizing the build-up of pressure behind. The collapsed gabions were found emptied by confirming the washing away of fines by the moving mass.

3. RASH^{3D} model

The back analysis of the aforementioned event was carried out using the RASH^{3D} numerical code (Pirulli, 2005; Pirulli et al., 2007). RASH^{3D} is based on a single-phase continuum mechanics approach and on depth-averaged St. Venant equations. This implies that both the depth and length of analysed flowing masses are assumed large, if compared to the characteristic dimension of the particles involved in the movement. The real moving mixture of the solid and fluid phases can therefore be replaced with a homogeneous continuum, whose rheological properties are intended to approximate the bulk behaviour of the real mixture, and the motion can be described using a model that consists of the balances of mass and momentum (Pirulli and Marco, 2010). Furthermore, assuming that the vertical structure of the flow (i.e depth) is much smaller than its characteristic length allows one to integrate the balance equations in depth and to obtain the so-called depth-averaged continuum flow model (Savage and Hutter, 1989):

$$\begin{cases} \dfrac{\partial h}{\partial t} + \dfrac{\partial\left(\overline{v_x}h\right)}{\partial x} + \dfrac{\partial\left(\overline{v_y}h\right)}{\partial y} = 0 \\ \rho\left(\dfrac{\partial\left(\overline{v_x}h\right)}{\partial t} + \dfrac{\partial\left(\overline{v_x^2}h\right)}{\partial x} + \dfrac{\partial\left(\overline{v_x v_y}h\right)}{\partial y}\right) = -\dfrac{\partial\left(\overline{\sigma_{xx}}h\right)}{\partial x} - \tau_{zx} + \rho g_x h \\ \rho\left(\dfrac{\partial\left(\overline{v_y}h\right)}{\partial t} + \dfrac{\partial\left(\overline{v_y v_x}h\right)}{\partial x} + \dfrac{\partial\left(\overline{v_y^2}h\right)}{\partial y}\right) = -\dfrac{\partial\left(\overline{\sigma_{yy}}h\right)}{\partial y} - \tau_{zy} + \rho g_y h \end{cases} \qquad (1)$$

where $\overline{v_x}$, $\overline{v_y}$ denote the depth-averaged flow velocities in the x and y directions (z is normal to the topography), h is the fluid depth, τ_{zx}, τ_{zy} the shear resistance stress (transverse shear stresses τ_{xy} are neglected), $\overline{\sigma_{xx}}$, $\overline{\sigma_{yy}}$ the depth-averaged normal stress and g_x, g_y the projection of the gravity vector.

Different rheologies exist to describe the basal shear that develops at the interface between the flowing material and the rough surface and are implemented in RASH^{3D}. As far as the Voellmy rheology is concerned, Rickenmann and Koch (1997) and Revellino et al. (2004) showed that this model, originally developed for snow avalanches (Voellmy, 1955), offers a good simulation of velocities for debris flows and debris avalanches. According to these authors and our experience, the Voellmy rheology was selected for the numerical back analysis of the July 18th event.

The Voellmy model combines a frictional term, which includes the friction coefficient μ (= tan φ, where φ is the friction angle) and a turbulent term, which includes the turbulence coefficient ξ:

$$\tau_{zi} = -\left(\rho g h \mu + \frac{\rho g \overline{v_i}^2}{\xi}\right)\mathrm{sgn}\left(\overline{v_i}\right) \quad \text{(where i=x,y)} \tag{2}$$

4. Dynamic analysis of the July 18th debris flow

The analysis of the July 18th debris flow is here presented. An attempt was made to investigate the influence of an abandoned building (Mi.No.Ter. in Fig.1b), located inside the storage basin, on the flow trajectory and dynamics. A set of numerical analyses in presence and absence of the Mi.No.Ter. building have been then carried out.

Both a Digital Surface Model (DSM) and a Digital Terrain Model (DTM) generated from LiDAR, with a 1m grid spacing of the pre-event topography, were provided by the Ministry for the Environment and Protection of the Territory and the Sea. The starting position of the 30,000 m^3 mass was the confluence of Ravina di Cancia with Bus del Diau torrent at 1335m a.s.l (Fig. 2). The Voellmy resistance model shown in Eq. (2) was used. The two Voellmy parameters were systematically adjusted until simulations approximately reproduced the observed distribution of deposits in the storage basin.

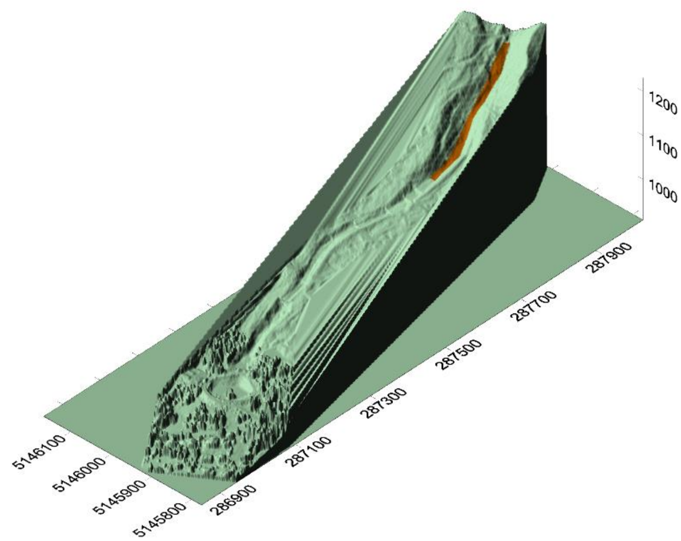

Fig. 2. RASH3D numerical simulation: starting position of the released mass on the topography.

The model provided a good match of the general extent and distribution of the storage basin deposit using a friction coefficient (μ) equal to 0.1 and a turbulence coefficient (ξ) equal to 300 m/s^2. A comparison between numerical simulations with the above calibrated parameters (Fig. 3b) and survey data collection (Fig. 3a) shows that the model reasonably simulates the event in terms of distribution of the final deposit.

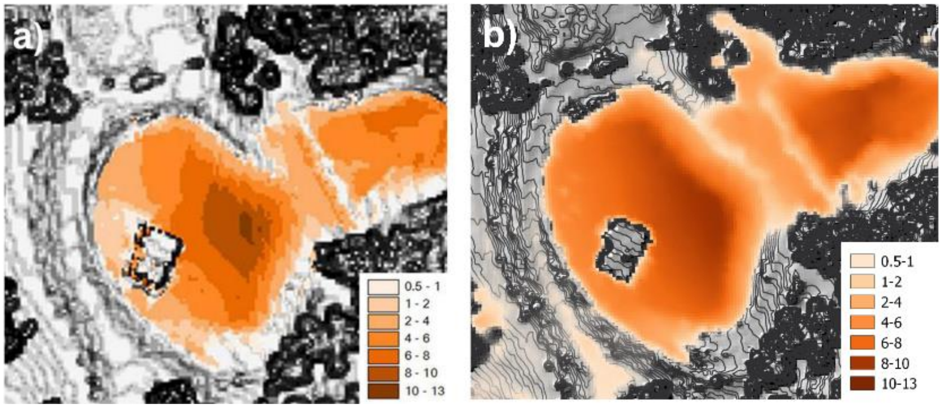

Fig. 3. Comparison between deposit depth as obtained processing pre- and post-event available digital topographic data (a) and RASH^{3D} numerical results (b).

Regarding the flow velocity (Fig. 4), it is observed that the flow reaches high velocity (>10 m/s) along the channel and in the upper part of the retention basin. The velocity decreases downstream of the gabion barrier to 5-6m/s.

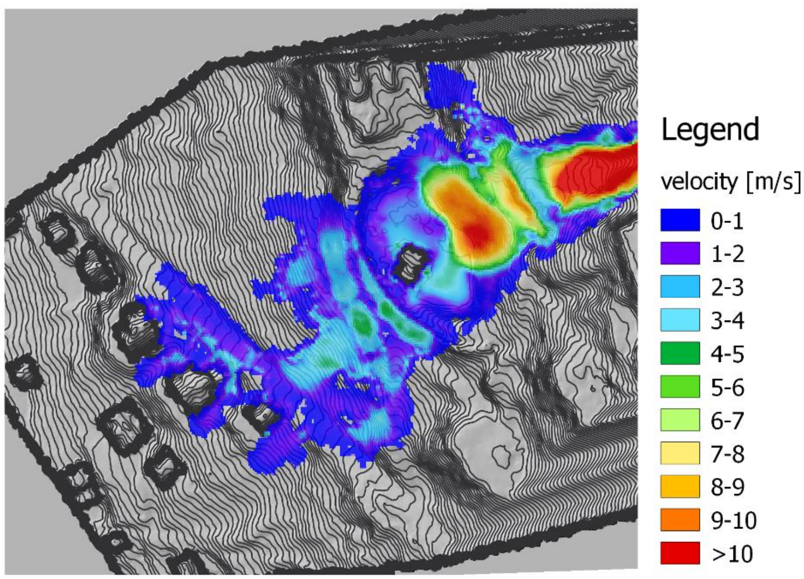

Fig. 4 RASH^{3D} numerical results: maximum computed flow velocity.

To highlight the role of the Mi.No.Ter building (Fig.1b) on flow dynamics, we modeled the flow with (Fig. 5a) and without (Fig. 5b) the building in the sediment basin. The results show that without the Mi.No.Ter. building, the flow would still have overflowed the storage basin (Fig. 5b, Scenario B). Nevertheless, a smaller quantity of material would have escaped from the storage basin and affected the downstream area. In particular, a lower height flow would have impacted the house below the debris basin where two people died. Based on the height of the windows, a lower flow height would have reduced the amount of flow into the house (highlighted with red squares in the legend of Fig. 5a and 5b). In particular, numerical results indicate a decrease of the flow thickness from a maximum value of 2 m (Fig. 5a, Scenario A in the presence of Mi.No.Ter.) to a maximum value of 1.4 m (Fig. 5b, Scenario B in the absence of Mi.No.Ter.). Results are justified by the fact that with the building, a larger quantity of material overflow the gabion barrier. While, without the house, the storage capacity of the basin increases and a minor quantity of material overflow the gabion barrier.

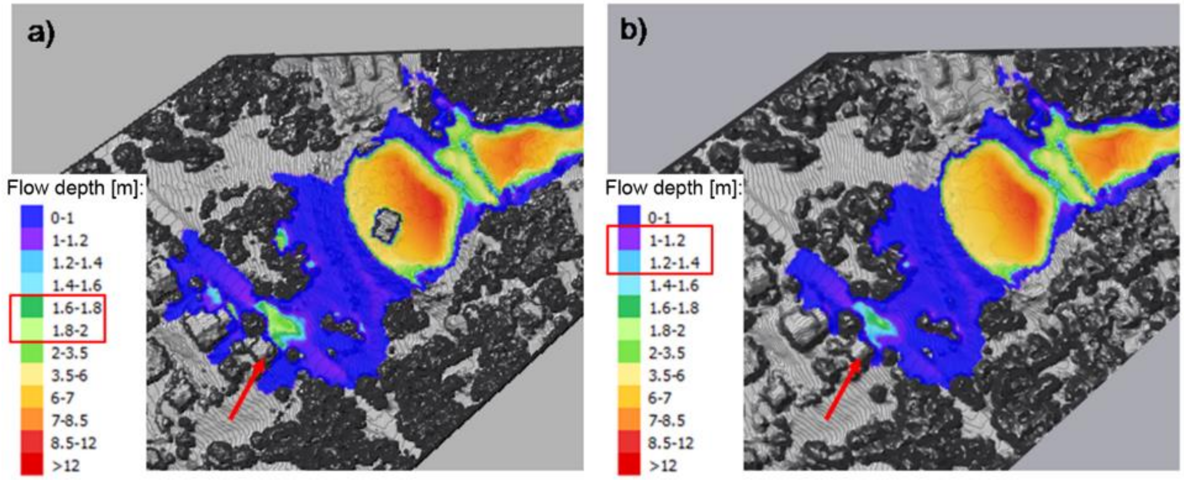

Fig. 5. RASH^{3D} numerical simulation: deposit depth distribution with (a) and without (b) the Mi.No.Ter. building. Red arrow indicate the position of the mainly impacted house during the July 18th event.

5. Conclusions

The design of countermeasures and the hazard zoning in debris-flow prone basins need an estimation of the debris-flow magnitude and require the understanding of the flow dynamic characteristics. With this in mind, the continuum mechanics based numerical code RASH^{3D} was used to investigate the role of a storage basin, built to protect the village of Cancia from regularly occurring debris flows, and of an abandoned building, located inside the above storage basin, on the dynamics and trajectory of the event here occurred on July 18th 2009. First, the calibration of the model parameters was made on the basis of the deposit shape and depth distribution surveyed on site. Simulations in presence and absence of the abandoned building were carried out and results compared. We found that removal of the building would not have prevented the mass from exiting the storage basin. But, without the abandoned building, the impact depth of the flowing mass would have decreased from about 2 m to 1.4 m. This would have reduced the flow of material into the house. Our results show that the RASH3D model can adequately simulate the complex flow dynamics of this event and, therefore, can be used quantify potential debris-flow impacts to infrastructure and inform the design of mitigation structures. Specific numerical analyses to investigate the partial collapse of the gabion barrier are foreseen in future.

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