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Modelling rock avalanche propagation onto glaciers

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ABSTRACT

Ice-rock avalanches which occur in glacial environments are controlled by the presence of snow and ice in the moving material and by possible propagation onto icy basal surfaces. All these factors contribute to enhancing the flow mobility. Mixing with ice and snow hampers block collisions and favours dense flow behaviour. Ice melting reduces granular friction by saturation of the basal material and fluidization effects. Propagating onto glaciers offers a smooth surface with low shear resistance.

This work is a review of the best documented ice-rock avalanches and focuses on evaluating their mobility for hazard analysis purposes by providing a set of calibrated cases. The rock avalanches have volumes ranging from $5*10^6$ m^3 to $25*10^6$ m^3. We replicate these events by using SPH and FEM numerical methods, assuming frictional and Voellmy basal rheologies. The Voellmy rheology best performs at replicating the landslide propagation. Among the back analyzed cases, the frictional coefficient ranges in the interval 0.03–0.1, the turbulent coefficient within 1000 m s^{-2}–2000 m s^{-2}. The bulk basal friction angle ranges within 2.75° and 14° with values inversely related to event volumes. Forward selection of the basal friction angle based on event volume, allows the replication of the Mount Cook ice-rock avalanche predicting a maximum runout which is less than 4% larger than observed. In the perspective of forward modelling, large uncertainty is related to the reconstruction of the post-event topographies, particularly for the sliding surface.

Mixing with ice and snow reduces basal friction proportionally to ice and snow content. Pure ice has a basal friction which is reduced by about 75% than basal friction of pure rock. Melting of ice during rock avalanche propagation has been evaluated for the Sherman event. The frictional heat generated at the glacier surface results in the melting of 86.2 ± 5.9 kg m^{-2}, which could have contributed to a minimum 20–35% ($\pm$10%) reduction of the material friction angle through the sole pore pressure generation within a 40 and 20 cm thick shear layer, respectively. The largest uncertainty is related to the area of contact between rock and ice.

1. Introduction

Ice-rock avalanches are rare but not uncommon in high-mountain regions and on rock slopes in permafrost conditions. In the perspective of risk analyses, rockfall and rock avalanches in glacierized mountain areas are attracting attention because of the large hazard they pose, the growing population in mountain areas (Pflaker and Ericksen, 1978), and the increasing number of events documented in recent years which are possibly related to climate changes and permafrost degradation processes (Haeberli et al., 1997; Deline, 2009; Evans et al., 2009).

Among landslides, rock avalanches are characterized by exceptional mobility and destructiveness. Their mobility is much larger than explained by the material behaviour and it is usually expressed by means of an "apparent" friction angle which is a-priori unpredictable. When a potential source of instability is identified, hazard mapping through runout analyses is necessary to define which areas could be threatened by landslide propagation. Nevertheless, due to the sudden evolution of the phenomena, and to the unfeasibility of using the measurable material properties in modelling, a gap remains in the selection of the input values introducing large uncertainty in modelling prediction. In theory, the H/L ratio (where H and L are the vertical and horizontal distances travelled by the debris) is used as an index of the rock/debris avalanche mobility (Fig. 1; Evans and Clague, 1988; Hayashi and Self, 1992; Siebert, 2002). In practice, H/L values obtained for historical events span widely due to the variability of the involved materials and to topographical constrains which are supposed to have strong influence on the mode of propagation (Strom, 2006).

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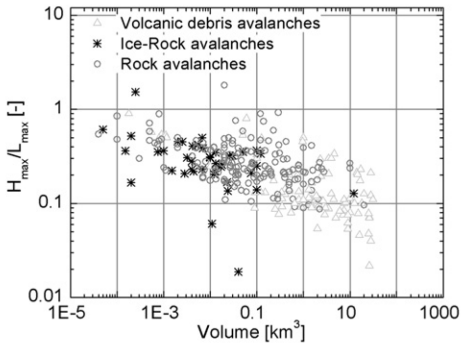

Fig. 1. Bilogarithmic plot of the relative runout (H/L) vs volume (V) of rock avalanches from different settings. Note the large scatter of ice-rock avalanche data.

The spread between the real material properties and their "apparent" counterpart is particularly high when the propagation evolves onto low resistant substrates, or involves weak rocks. Particularly for rock avalanches that travel onto glaciers long runouts are possibly explained by (1) low friction at the debris–glacier interface (Evans and Clague, 1988), (2) presence of ice and snow within the propagating material which can fluidize the mass (McSaveney, 1978) eventually transforming the mode of propagation from almost dry rock avalanches into debris flows (e.g. Huascaran, Pflaker and Ericksen, 1978; Kolka, Evans et al., 2009) and (3) increasing saturation at the base of the flow due to frictional heating or compression of snow along the glacier surface (Geertsema et al., 2006). All these factors result in 25% higher average mobility of ice rock avalanches compared to non-glacial events of comparable magnitude (Evans and Clague, 1988; Huggel et al., 2005).

In this paper, we investigate the mobility of rock and debris avalanches evolving in glacial environment by providing a set of calibrated cases. We select some of the best documented case histories to be back analysed by SPH (i.e. *Smoothed Particle Hydrodynamics*; McDougall, 2006) and FEM (i.e. *Finite Element Method*) codes. The events develop in a variety of settings and conditions and vary with respect to their morphological constrains, materials, contact surfaces, and styles of failure. The event reconstructions and the back analyses are based on the observations available from the literature (i.e. runout distance, impacted areas, flow velocities, deposit thicknesses). We test the performance of the frictional and Voellmy rheologies to define a range of parameter values which best replicate the propagation of the selected events. The back analysed parameters provide a range of values to be used for the forward analyses of possible future events evolving in similar conditions.

2. Features of rock avalanches propagating onto glaciers

Ice-rock avalanches usually initiate as slides, topples and falls. The major factors promoting rock slides and avalanches in high-mountain regions are (i) seismic shaking (Post, 1967; Jibson et al., 2006) which often trigger clusters of rock avalanches, as documented for historical earthquakes which involve large mountain walls (e.g. Hewitt et al., 2011); (ii) glacial deepening and rock-slope steepening since the last glacial maximum (Augustinus, 1995; Ballantyne, 2002); (iii) progressive permafrost degradation by changes induced in rock mass temperature and water availability by warming hanging glaciers (Haeberli et al., 1997; Geertsema et al., 2006); and (iv) debuttressing of rockwalls due to glacier retreat (Agliardi et al., 2001; Ambrosi and Crosta, 2011).

While descending very steep slopes, rock avalanches initially attain velocities generally higher than 60–70 m s^{-1} (Sosio et al., 2008), eventually approaching 100 m s^{-1} (Shreve, 1966; Huggel et al., 2008). Average velocities within 40–50 m s^{-1} are inferred from the total duration of seismic signals produced by the propagation (McSaveney, 2002; Schneider et al., 2010). Similar velocities can be locally reached by non-glacial rock avalanches (e.g. the runup height observed for the Val Pola rock avalanche required velocities as high as 78–108 m s^{-1}; Crosta et al., 2004). High initial velocities eventually lead the debris to rise hundreds of meters up topographic obstacles, to travel very long distances onto generally very low slope gradients of the glacier surface (Post, 1967) and favours erosion processes. Once they impact the glacial ice, they transform their style of motion to flow (Schwab et al., 2003) eventually entraining large volumes of ice and snow (McSaveney, 1975, 2002). The overall mobility is significatively enhanced by travelling on glacier surface as show by empirical observations (Evans and Clague, 1988) and numerical simulations (Huggel et al., 2007). Maximum runout distances are commonly five to ten times the fall height; nevertheless, these may be altered considerably depending on event volume and emplacement morphology. Rock avalanches propagating onto glaciers are mostly unimpeded by topography; being weakly or not confined, and they offer the possibility of observing morphological features only slightly influenced by the smooth, icy surface. Lateral confinement within moraines can enhance the mobility by a funnelling effect as documented at Little Tahoma Peak (Fahnestock, 1978) and at Huascaran (Pflaker and Ericksen, 1978).

The deposits are generally tongue shaped with digitated margins and with minor surface relief. When not constrained, they spread out over large areas and deposit as relatively thin sheets of crushed, pulverized debris (Fig. 2), generally 2–3 m thick after the complete melting of the snow and ice component (Deline, 2008). Rarely, deposits more than 2–10 m thick were locally measured (Hewitt et al., 2008; Reznichenko et al., 2011). These values are generally much lower than those typical for rock avalanches on soil/rock surfaces. Available data indicate amounts of ice and snow in the deposits which vary from being negligible (e.g. Thurwieser rock avalanche, Sosio et al., 2008) to representing up to 60%–75% (e.g. events occurred at Illiamna, Steller, Brenva glaciers; Deline, 2001; Huggel et al., 2007; Deline and Kirkbride, 2009).

Typical deposit features may develop, and some of them are shared with rock avalanche in non-glacial conditions, which are either controlled by the high emplacement velocity or interaction

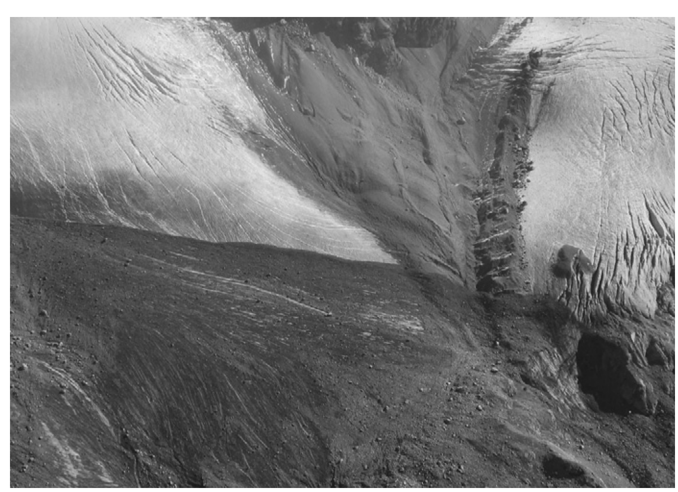

Fig. 2. Aerial view of the Zebrù Glacier (Valfurfa, Central Italian Alps) which is partially covered by debris deposits. At the photo bottom, the glacier is mantled almost continuously by a fan shaped, thin sheet of debris deposited by the rock avalanche. At the photo top, the glacier is covered by the more irregular and thicker accumulation of glacial debris. Note a thin layer of dust which buffer the uppermost part of the rock avalanche deposit (photo by M. Ceriani).