Landslides falling onto a shallow erodible substrate or water layer: an experimental and numerical approach

GB Crosta\textsuperscript{1}, FV De Blasio\textsuperscript{1}, M Locatelli\textsuperscript{1} S Imposimato\textsuperscript{2} and D Roddeman\textsuperscript{2}

\textsuperscript{1}Department of Earth and Environmental Sciences, University of Milano Bicocca, Italy.

\textsuperscript{2}FEAT, Netherlands

E-mail: giovannibattista.crosta@unimib.it

Abstract. Landslides often collapse in areas covered by alluvial deposits forming an erodible layer. This erodible substrate may deform plastically under the intense shear stress of the landslide mass. In other cases, the collapse occurs onto a water basin or tidal flat, creating impulse water waves whilst the landslide may be lubricated by a water layer underneath. In either cases the presence of a medium underneath the landslide will change its dynamics introducing complex processes. While frictional, dry masses and taluses generally hamper the landslide motion. In this work, we present some experiments mimicking the collapse of a landslide onto shallow erodible or water layers. The landslide is simulated with a granular material (sand or gravel) flowing on an incline (35-66°) followed by a horizontal sector covered with a granular bed 1 to 2 cm thick or with a 0.5-1 cm of water. Monitoring evolution in time allows us to describe in detail the process of fluidization of the material at impact, the generation of impact waves, and the erosion process. Concerning impact on a sand layer, the apparent friction coefficient (H/L) is found to increase with the chute slope angle and with the thickness of the erodible layer, and to decrease with the volume. At low slope angles, the material accumulates backwards in a shock wave mode, while at larger slope angles (>45°) it accumulates by prograding forward. A granular avalanche falling from the slope is partially reflected at the sharp slope break where erosion occurs and then propagates initially as a wave partially eroding the superficial material. Folding and thrusting occur within the dense shear flow and the erodible layer. Experiments with a water layer show that the dynamics depends much on the permeability of the granular avalanche. FEM numerical simulations replicate and allow to describe and understand both the spreading and the erosion, and internal deformation recorded in the erodible layer. Experimental findings are compared with real rock avalanches, flowslides and snow avalanches characteristics and morphological features. A medium with low permeability may be lubricated by the presence of water, resulting in a front acceleration and a final double-ringed deposit.

1. Introduction

Field studies and observations on the behavior of a landslide collapsing onto erodible substrates are scarce even if it is known that presence of a medium with very different characteristics may be
extremely important in modifying the further flow of the landslide. Because the erodible substrate remains completely sheltered underneath the landslide mass, a closer examination is difficult (Hewitt, 2006; von Poschinger and Kippel, 2009). In other cases, the erodible substrate has been pushed ahead of the landslide and its flow is studied in detail. At Arvel (Switzerland) a large rockfall–avalanche (1922) pushed alluvial sediments forward, folding them (Choffat, 1929; Jaboyedoff 2003; Crosta et al., 2008) in a tectonic style, with arched ridges and grooves up to 7 m high. The average slope angle was 63.3° for a drop height, H, of 240 m and maximum runout, L, of 337 m (H/L = 0.71). Accounting for this frontal material as if it belonged to the landslide itself would correspond to a total H/L of 0.35 (Crosta et al., 2009). Other examples of collapse on a flat area are those of the Frank landslide (H = 600 m, slope angle = 47°), the Ollague landslide (Crosta et al., 2013, H = 707 m, angle 38.2°, total H/L = 0.25), the dry Las Colinas landslide (Crosta et al., 2005) collapsed along a 30-35° slope (H = 160 m, L = 715 m, H/L = 0.22).

Ancient rock avalanches were affected by a basal erodible layer (McSaveney et al., 2000) like at Flims (Switzerland) where alluvial material of the Bonaduz Gravel Formation is cut by Pavoni tubes suggesting the presence of pressurized fluids in the basal layer (Erismann and Abele, 2001; Von Poschinger, 2006). The wet alluvial sediments are considered a cause for the extraordinary propagation of the Flims landslide. The Marocche (Trentino province, northern Italy) are examples of landslides collapsed on flat alluvial areas in prehistoric or historic times. Some of them dammed locally the drainage system, creating enduring lakes as in Molveno (H = 1100 m, slope angle = 45°).

Similar geometrical constraints have been observed along many Martian slopes of the Valles Marineris gorge (Lucchitta, 1979). We will show that this choice of the geometry leads to interesting predictions for the mobility of the landslides.

The importance of the properties of the basal sliding layer becomes apparent for landslides falling onto glaciers. Numerous case studies, such as Sherman in Alaska (Post, 1967; McSaveney, 1976) and the Thurwieser peak in Italy (Sosio et al., 2009), show that the friction coefficient may decrease by one order of magnitude due to the melting of ice (Schneider et al., 2011; Sosio et al., 2012; De Blasio, 2014). Moreover, the dynamics of such events may be relevant in reconstructing the past environment of Mars, since the presence of a lubrication layer of some sort has been invoked to explain the extraordinary mobility of landslides on the red planet (Lucchitta, 1979; De Blasio, 2011).

A peculiar situation concerns the collapse onto a water basin such as a lake, river, or the sea. We focus on landslides collapsing on very shallow water like a tidal flat, where water provides a thin lubricating medium, rather than the case of large landslides plunging inside deep basins (Crosta et al., 2015). Most events recorded on shallow waters involve chalk cliff collapses onto flat tidal areas in northern Europe (Hutchinson, 2002; Dupperet et al., 2006; Günther and Thiel, 2009), but also large volcanic rock avalanches travelling into lakes (Sosio et al., 2011). Recognizing that vertical failures result in shorter runouts than those occurring along a more gently slope, Hutchinson (2002) suggests that the former involve harder and less porous rocks, perhaps less prone to water remolding. However, the abrupt slope change and the possible role of the water layer in the dynamics are not considered.

The physical processes occurring when a landslide collapses onto an erodible layer or water have not been studied systematically both from a geological viewpoint and concerning the mechanics of flow. Firstly, there is a physically-related problem directly linked to the hazard assessment. The entrainment of the underlying material results in an increase of the overall volume of the moving mass and likely decreases the velocity of the landslide as a consequence of momentum conservation. Thus, it is uncertain whether a landslide entraining an erodible substrate will be more dangerous as consequence of the increased mass or a sudden change in behavior, or less dangerous because of its diminished speed. Moreover, the erodible sediments in front of a potential landslide may act as a protective buffer, decreasing the mobility, or as a lubricant (see next point) or even jetting ahead of the landslide, splashing inhabited zones.

Secondly, the rheology of the erodible layer plays an important role. While some kinds of material (e.g. cohesive, highly frictional, dry masses) may perhaps hamper the movement of the landslide (see Crosta et al., 2008, 2013b), others such as water-rich alluvium, glacial material,
cohesive silt and clay, loose saturated fine sands, may act sometimes as a lubricant, transferring the stress from the frictional base to a weaker layer. In terms of final fate of the eroded material, it can be entrained, dragged, sheared, ploughed, bulldozed by the landslide, or even remain unaffected if the base of the landslide is strongly decoupled from the substrate material due to the presence of lubricating material.

Numerous experiments have been performed to reproduce the collapse of landslides and or in general geophysical granular flows (Denlinger and Iverson, 2001; Forterre and Pouliquen, 2008; Lacaze et al., 2008; Lajeunesse et al., 2004, 2005; Mangeney et al., 2007, 2010; Crosta et al., 2008, 2013). These experiments investigated the flow of a granular medium along a flume under controlled conditions while monitoring the flow velocity, change in time of the shape of the travelling mass, and the examination of the final geometry. Most experiments concentrated on the final shape of the deposit or the evolution on smooth surfaces (e.g. Gray et al., 1999; Pudasaini and Hutter, 2006) while fewer have so far been devoted to the flow onto a bed of granular material (Dufresne, 2012; Crosta et al., 2008; 2009; Farin, 2014; Rooley, 2011) and no experiments — to our knowledge — on a thin water layer.

In this work, we simulate a landslide with a series of experiments in which a small-scale granular flow collapsing onto an erodible layer or shallow water. The variety of natural geological processes and topographic situations implies that many different kinds of erodible layers may affect the flow of real landslides. Transferring these situations from the field to the laboratory, we envisage four possible interesting layer types to use in the experiments (Table 1).

1. A **dry granular bed** is the simplest possible system. A granular material endowed of Mohr-Coulomb frictional behavior may affect the friction coefficient at the base of the landslide. In the field, such system may be a reasonable model for landslides falling onto dry rock debris. The particle size, shape, and angularity as well as the soil bulk density can control the consequent behavior.

2. More dramatic changes might be expected if the entrained material has fundamentally different rheological properties. A material of **low shear strength**, especially if **water-rich** may severely affect the behavior of the overlying mass. From the experimental point of view, this situation requires a wet and slightly cohesive erodible layer behaving as a sensitive clay. This may be a good model for rock avalanches falling onto alluvial sediment (Hungr and Evans, 2004; Chen et al., 2006; McDougall, 2006; Crosta et al., 2008, Crosta et al., 2013b). Needless to say, in an attempt to simulate alluvial materials the complexity of the erodible experimental material may easily escalate. For example, layering, porosity and compaction, permeability, coarse versus fine fraction relative content, frictional and cohesive properties, particular rheological behaviors (e.g. liquefiable, dilatant, drained/undrained) will likely control the quantity of material affected by the landslide motion and its response.

3. A **water layer** may be used to simulate the collapse of a landslide onto a shallow water layer, a tidal flat, or a lake.

4. The collapse onto **ice** cannot be easily simulated in the laboratory not only because it would force the experimenter to a low temperature setting (Schneider et al. 2011), but also because the stress developed by a simulated small-scale laboratory flow is insufficient to re-create significant effects at the base of a real landslide travelling on ice and ice melting. Although for completeness, we mention ice as an important natural lubricant for landslides in glaciated environments, experimentation with this material will thus not be conducted in this work.

We present a set of results with controlled experimental tests in which dry sand or gravel reaches a horizontal plate where an erodible layer of sand (point 1) or a thin water layer (point 3). The real material conditions and the relative experimental settings are summarized in Table 1, while those with low shear strength material (point 2) and ice (point 4) are deferred to a later study.
Like in other experimental tests, we utilize a bi-linear geometry consisting of an inclined plate followed by a horizontal portion. This is a simple geometry to use in the experiments and data analysis, and as described above it is also a good model for the geometry of many rock avalanche collapses (De Blasio and Crosta, 2015) (Fig. 1).

![Figure 1](image_url) Some field examples of landslides collapsed onto flat area covered with a medium. A: Frank slide; b) Pordoi Pass, Dolomites; Dover, Chalk cliffs; d) Oberschutt, Austria.

We will show that this bi-linear geometry affects significantly the results of the experiments because the impact at high velocity of the granular flow with the basal horizontal layer/board influences the further dynamics more than previously appreciated, with effects that may find an equivalent in real rock avalanches.

### Table 1 – Possible erosive layers onto which landslides may collapse and experimental analogs.

| Type of erodible layer | Geological setting | Examples | Experimental analog | This work |
|------------------------|--------------------|----------|---------------------|-----------|
| Dry granular           | Colluvium          | Talus in dry climates (Crosta et al., 2014) | Sand      | Yes       |
| Wet cohesive           | Wet alluvium, tidal flat | Arvel (Jaboyedoff 2003; Crosta et al., 2008) | Sand and wet clay | No       |
| Water                  | Shallow water      | Chalk collapses in northern Europe (Hutchinson, 2002; Dupperet et al., 2006) | Water     | Yes       |
| Ice                    | Glacier            | Landslides on glaciers (Post, 1967; McSaveney, 1976) on permafrost, probably on Mars | Ice      | No. The basal shear stress of experimental granular flow too low to produce ice melting |

### 2. Experiments

#### 2.1. Experimental setup

The experimental setup consists of a smooth board (1.2 m long) with possibility of setting a desired slope angle between 30° and 65° (Fig. 2). A box containing the granular material is fixed at the upper end of the plate. A mechanical gate controlled by a couple of springs is used to release the material.
The gate opening time, much shorter than the collapse time of the granular material, as checked by multiple testing with high speed video recording, ensures a negligible influence of the mechanism of release. The tilted plate is joined to a smooth horizontal sector where the flowing material come to rest. The plate may be covered by the erodible layer (Fig. 2B). For experiments with water, the plate is made impermeable and filled uniformly with a water layer. Two Plexiglas side boards allow a direct observation of the experiments from the sides, beyond the lateral confinement of the material. Two high speed cameras (60 frames/s and 600 frames/s) and a laser profilometer (profiling frequency:120 Hz) placed in front of the apparatus are used for monitoring the flow characteristics, and the flow evolution in space and time.

Figure 2. The experimental apparatus consists of a release box where the granular material is placed, a slope along which the flow takes place, and an horizontal basin which may or not be filled by erodible sand or water. The high speed video and laser profilometer are computer-controlled.

The erodible sand layer is positioned by hand pluviation and then leveled avoiding further compaction. The adopted materials consist of uniform Hostun silica sand ($C_u = 1.57$; $D_{50} = 0.32$ mm; mean unit weight $= 1.42$ g/cm$^3$) or rounded gravel for both the released mass and the erodible layer. In some experiments, we used subangular/subrounded gravel ($C_u = 1.5$; $D_{50} = 2.5$ mm; mean unit weight $= 1.48$ g/cm$^3$) for the granular flow. Released volume varies between 1.5 and 9.6 liters. The physical and mechanical parameters of interest to these experiments are reported in Table 2.

Table 2 - Physical and mechanical properties of the granular materials used in the experiments. The friction angle has been assessed by: i) depositing sand cones on different surfaces (smooth or sanded wooden board) and surveying their geometry and inclination by a high resolution laser scanner, ii) inclining a board with a homogeneous sand layer till avalanching was observed, and iii) direct shear testing.

| Material  | Angle of repose ($)  | Angle of avalanching ($) | Internal friction angle ($) direct shear test | Mean Bulk Density (g/cm$^3$) | Use in the experiments |
|-----------|---------------------|--------------------------|---------------------------------------------|-----------------------------|------------------------|
| smooth    | 31                  | 25.4                     | peak                                        | 1.42                        | Erodible layer         |
| sandy     | 33                  | 31.7                     | residual                                    |                             |                        |
| Hostun    | 30                  | 31.7                     | 37.7                                        | 1.42                        |                        |
2.2. Experimental results

2.2.1. Bulk experimental deposit

Figure 3 shows the experimental deposit obtained with two different slope angles, $\theta$, of 40° and 60°, without the erodible basal layer. Even though the runout increases with the slope angle, it should be remembered that the fall height increases, too. A better characterization of the mobility in terms of the ratio between fall height and runout will be considered in the next section. The bulk, triangle-shaped thick deposit at the slope break exhibits a series of transversal grooves and furrows. In case of a smooth surface (e.g., Plexiglas rather than wood) and high sloping angle, the tail of the deposit detaches completely from the sloping ground and the slope break, with a very elongated deposit profile. The presence of the basal erodible layer causes a shape change of the deposit, which becomes lunete with steeper lee-ward and up-ward sides. Moreover, the erodible layer decreases the runout compared to the case of smooth slope. A decrease in inclination of the sloping part of the path is associated to deposits progressively propagating uphill in a triangular shaped and stepped deposit.

![Figure 3. Aspect of the final deposit of some experiments and corresponding laser profiles at different times during the accumulation at two different slope angles: 40° (left) and 60° (right).](image)

The inclination of the frontal part of the deposit decreases progressively (e.g. 22.4° to 14.8° in Fig. 4) with the increase in slope angle (45° to 60°, in Fig. 4), suggesting that a different mechanism reshapes the frontal part of the deposit in the last depositional phase. A much less inclined front is observed in the case of propagation on a smooth horizontal surface (e.g. 9.8°), the upstream facing side of the deposit maintaining approximately the same inclination through the various tests (e.g. 16.9° to 17.4° with the erodible layer and 19.2° on smooth base in Fig. 4). All these values are well below the angle of avalanching as determined for this material by laboratory tests (see table 2). Furthermore, the smoother superficial morphology for the deposits is very well shown by the slope angle along the
deposit profile, where for the case of the $45^\circ$ slope without basal layer the change in slope angle occurs smoothly along the entire deposit length. Some interesting observations about the final morphology of the deposit can be done when coarse gravel is released instead of using Hostun sand. Similar to the case for the sand flows, the deposit grows upslope with decreasing slope angle, resulting in a rough conic geometry with the apex aligned with the deposit centerline. The deposit length increases slightly with the slope angle but not the total horizontal distance. While at low slope angles some of the gravel outruns the bulk deposit, an increase of slope produces a wedge of material pushed or upraised well in front of the coarse material (Fig. 4).

**Figure 4.** Change in the style of accumulation of the granular flow as the slope angle is progressively increased for experiments with Hostun sand.

Figure 5 shows the difference between an experiment without (a) and with (b) erodible layer. Note that the presence of the layer changes the style of deposition and at the same time decreases the runout.

2.2.2. Interpretation of the bulk experimental deposit

It is customary to introduce the Fahrboschung (FB) as a proxy for the mobility of a landslide or an experimental granular flow. The FB, which is equivalent to the apparent friction coefficient encountered by the granular mass during the flow (Scheidegger, 1973), is defined as the ratio $H/L$ between the vertical drop ($H$) and horizontal spread ($L$) of the landslide, calculated adopting as initial point the rear end of the mass prior to failure, and as end point the maximum distance reached by the tip of the failed mass. Results for an experimental mass show that this ratio is close to the friction coefficient of the granular-bed interface (Erismann and Abele, 2001). The value of the FB ratio can be affected by an initial granular mass positioned with very high aspect ratio (Lajeunesse et al., 2004, 2005; Lube et al., 2005; Crosta et al., 2009; Lucas et al., 2014) because part of the available energy derives from the potential energy of the column. However, this effect is minimal in this study because the ratio between the vertical size of the containing box and the vertical fall of the center of mass is very small.
Figure 5. Difference in the style of deposition of a sand granular flow between: a) smooth base, and: b) a sand layer is present. Arrows represent the general trend of evolution of the flow/deposition.

Figure 6 shows the FB of the granular mass as a function of the different slope angles for our experiments with both different granular materials and different basal materials. Note that in all cases the FB increases with the slope angle, indicating lower mobility. We explain this effect noticing that at the slope break most of the vertical component of the momentum is transferred to the earth surface and is lost. Note also that this systematic data confirms that the presence of an erodible layer increases the ratio H/L.
In the absence of an erodible layer, it is assumed that the horizontal component of the granular flow momentum is conserved at the slope break, but the vertical one is absorbed at the break of slope. We also assume that, due to the irregular bouncing on the horizontal surface, part of the vertical momentum is transformed into horizontal momentum. This component sums up as a fraction $\varepsilon$ of the vertical component of the velocity, where $\varepsilon$ is a coefficient of restitution. The final equation for the velocity of the front immediately after the break of slope is

$$U_x = \sqrt{2gL'(\sin \theta - \mu \cos \theta) + (\cos \theta + \varepsilon \sin \theta)}$$ (1)

where $L'$ is the board length. The run-out on the horizontal board can be calculated as

$$R_H = \frac{L' \sin^3 \theta}{\mu} \left[ \left( 1 - \frac{\mu}{\tan \theta} \right) \left( \frac{1}{\tan \theta} + \varepsilon \right)^2 \right]$$ (2)

and the total length travelled (first on the inclined board, then on the horizontal area) becomes

$$R = L' \cos \theta + \frac{ug}{2g\mu}$$ (3).

Considering that the vertical drop is $H = L' \sin \theta$, the relationship for the ratio between the total drop height and the runout becomes
\[
\frac{H}{L} = \frac{\tan \theta}{1 + [\cos \theta + \epsilon \sin \theta]^2 \left(\frac{\tan \theta}{\mu} - 1\right)}
\] (4)

Eq. (3) shows that the ratio \(H/L\) increases monotonously with the slope angle, implying that a landslide from a steep terrain loses mobility at the slope break compared to one travelling on a smoothly varying terrain.

Figure 6 shows also a comparison of our experimental data and the relation (4). Evidently, the simple model is capable of capturing some of the dynamics at the slope break. We come back to this plot in the section devoted to the comparison with field data.

We now consider the decrease of mobility and thus an increase of friction coefficient resulting from the experiments in the presence of an erodible layer. The acceleration of the center of mass of the granular mass along the ramp is:

\[
\frac{du}{dt} = g (\sin \theta - \mu \cos \theta)
\] (5)

where \(\mu = \tan \phi\) is the friction coefficient. The flow reaches the lower plateau with a velocity

\[
u_0 = \sqrt{2gR(\sin \theta - \cos \theta \mu)}
\] (6)

where \(R\) is the inclined runout length. In the absence of the erodible substrate, the velocity as a function of the position \(x\) along the horizontal plate would be obtained by integration of

\[
\frac{du}{dt} = -\mu g
\] (7)

which gives

\[
u = \sqrt{\nu_0^2 \cos \theta - 2g\mu x}
\] (8)

where \(x=0\) corresponds to the position of the slope break. In the presence of the erodible layer, the granular mass entrains part of the layer down to a depth \(D'\), accelerating the eroded material to a finite velocity. For momentum conservation, this implies that the total velocity of the mass after entrainment \(u_{\text{entr}}\) must decrease. After the collapse upon the horizontal plane, we will have:

\[
u_{\text{entr}}(M + M') = \nu_0 \cos \theta M
\] (9)

\[
M = SD\rho; \quad M' = SD'\rho
\] (10)

where \(S\) is the basal surface area of the flow, \(\rho\) the bulk density of the granular material, \(D\) and \(D'\) are the flow thickness before and after entrainment, respectively, and \(M\) and \(M'\) the respective masses. The velocity as a function of the position is as

\[
u = \sqrt{\nu_{\text{entr}}^2 \cos \theta - 2g\mu x}
\] (11)

We find that the horizontal runout of the mass in the presence of the erodible layer \(L'\) is diminished with respect to the case of no layer \(L\), which gives an apparent friction coefficient increasing like

\[
\mu(D') \approx \mu(D = D)[1 + \frac{\nu_0^2 \cos \theta D'}{g\mu R D} \approx \mu(D = D)[1 + 0.2 \frac{D'}{D}]
\] (12)
It is found that 1 cm of erodible material may result in a 10-20% increase of the apparent friction coefficient. Thus, if the friction angle without erodible bed is about 30° (see Table 2), a 1 cm-thick erodible layer increases the apparent friction angle to about 34°, which is close to what observed for example for the curve in Fig. 6.

Note that the apparent friction coefficient appears to saturate as a function of the erodible layer thickness. This indicates a limit depth $D_{\text{MAX}}$ of granular material that the material can entrain.

2.2.3. Erosion and thrust structures in the experimental deposit
To understand the geometry of the internal displacement, we have inserted some colored layers within the basal sand and studied how the whole sand deposit was deformed by the impact and deposition of the granular flow (Fig. 7a). Three layers of Hostun sand are prepared in this way (from bottom to top): uncolored, orange, and blue. Even when colored, the sand maintains the same mechanical characteristics. After the experiment performed releasing a granular (uncolored) Hostun sand at 66° slope, the resulting deposit has been wetted to provide the cohesion necessary for cutting sections through it.

![Figure 7](image)

Figure 7. Top: experiment in which one light blue and one orange layer of sand are sandwiched between uncolored sand (initial configuration schematized in d). b) and d) cross sections cut through the deposit to show the internal structure of the deposit. e) and f) scheme of the impact phase and erosion with formation of a sand jet and final geometry of the deposit with internal structures.

The orange layer appears locally doubled in sections both parallel and perpendicular to the direction of flow. The blue layer appears folded and sheared, and locally sandwiched between the two and with a clear increase in thickness and an upper irregular limit (Fig. 7). Figures 7b) and 7c) evidence the lack of both the colored layers in the upstream side of the deposit suggesting the erosive action played by the granular flow descending the slope and hitting the basal layer. The blue layer seems eroded and redeposited along the basal movement surface. On the other hand, the orange layer at the foot of the slope has been stripped and entrained inside the flow, remaining inside the upper cap of the travelling mass and partially inverting the stratigraphic sequence (orange–blue-orange in Fig. 7e). In some of the longitudinal cross cuts multiple shear planes, associated thrust fold-like features have been observed.
Experiments at low slope angles, in which the granular flow cannot dig deeply enough into the granular bed, do not produce layer doubling.

2.2.4. Numerical models
Such experiments show in a very direct manner the complexity of the final product of erosion, but are not capable to show how erosion occurs. Examining the colored experiments with a high-speed camera is not much useful, since the processes underneath the erosive layer are obviously hidden by the granular flow itself. For this reason, we ran 2D numerical simulations for the same situation using a finite element code (Roddeman, 2011, see Appendix A for a basic introduction). The results (Fig. 8) show clearly the generation of a steep front and a jump of the avalanche flow above the basal layer.

![Figure 8](image)

Figure 8. Numerical 2D simulation of the erosion process. Progressive erosion, folding, internal shearing and deposition are shown at three successive time steps.

The basal layer is pushed away at the front of the avalanche, along a steep contact surface, and starts to be eroded from the surface and folded at depth (Fig. 8a). The upper part of the front starts climbing up against the basal sandy material, along a steep and straight shear band, and to overpass the crest generated in the basal layer. In figure 8b) the decreasing velocity of the material climbing at the front and eroding the layer can be observed, as well as the high velocity of the material still rushing down the slope and pushing the front from the back. The maximum velocity at the impact is about $3.2 - 3.5 \text{ m s}^{-1}$ computed by assuming a basal friction angle of $25^\circ$ ($3.57 \text{ m s}^{-1}$) and $31^\circ$ ($3.44 \text{ m s}^{-1}$).

Note how the simulations clearly show that the front of the avalanche material, slowed by the folding basal layer, is completely overturned and the blue layer is doubled (Fig. 8c). The velocity vectors
suggest that the evolution of the flow overriding the basal material in a sort of front instability. The final two steps of the simulation are characterized by the elongation of the deposit and of the S-shaped contact band between the avalanche material (light blue) and the overturned basal layer.

2.2.5. Experiments with water
Experiments with water layer have been performed with flows of Hostun sand or rounded gravel falling onto a 0.5 or 1 cm thick water layer. The results in Fig. 9 with sand show the formation of a raised margin upon impact with water. Water shoveled at the front is thrust sideways and propagates in ripples away from the impact region, depriving the travelling sand of some of its energy. A sort of hydroplaning starts, whereby the granular flow floats at the top of the water layer, which prevents friction against the base. However, hydroplaning ceases after a run of few centimeters, after which sand plunges progressively to the bottom of the pool and comes to rest. The three phases can be seen also in the spatiotemporal diagram (Fig. 9d).

The dynamics of impact with water, even in a relatively simplified experimental setting like the present one, may be fairly complex. Hydroplaning in a material with relatively low permeability like fine sand is likely to be initiated by the impact force against the water surface. The pressure at the surface of water is of the order

\[ P = \frac{1}{2} \rho_W U^2 \]

where \( \rho_W \) is the density of water and \( U \) is the velocity of the granular flow against the medium. The impact force bouncing the granular medium upwards is proportional to \( P \) and to the area \( A \) of the surface in contact with water. Because the force of impact \( F = P A \) is greater if the impact is oblique rather than head-on (since the area of contact is larger), the granular flow colliding with water at a skewed angle may be thrust upwards by the impact and thus remains at the water surface for a certain time before collapsing to the bottom of the pool.

Figure 10a shows the final deposit obtained after removing the water from the pool. Note the double-ringed appearance where the deposit appears in two ropes with absence of deposition in between. The frontal ring may be the remnant of the frontal hydroplaning portion on the fast frontal wave. Some gravel particles detach from the rest of the granular flow, as is also evident in the filmed sequence. A comparison with real deposits is intriguing. Fig. 10b reproduces in greater scale the same deposit as in Fig. 10a.
Figure 9. Experiment with a granular flow of Hostun sand onto a shallow water layer at three successive time steps (from a to c). a) post impact phase with frontal part raised above water; b) advancing front with frontal water wave and irregular bumpy front surface; c) well developed frontal wave partially washing back on the deposit and progressive grow of the deposit by successive small waves recognizable as shallow fronts. In this phase water appears through the dry sand at the front. d) Spatiotemporal diagram for the previous experiment showing the first front arrival (0) and the three successive phases a to c.

Note the similarity with the experimental deposit (Fig. 10a), showing that the formation of a double ring may occur also in actual cliff collapses onto a tidal flat. The head detachment in subaqueous landslides and debris flows is well known both from pool experiments and is commonplace in some clay-rich subaqueous debris flows (e.g., Ilstad et al., 2004). However, to our knowledge this is the first time that a similar head detachment is obtained for granular flows collapsing on thin water.

We also simulated the collapse of the sand flow onto a thin water layer using the same FEM-ALE 2D numerical model used for the simulation of sand onto sand experiments. The results in Fig. 11 show the formation of a water layer underneath the granular medium. Note that the water is endowed of pressure field in the simulations, so that the calculations can take into account the stagnation pressure, which is at the origin of hydroplaning (Mohrig et al., 1998).
Figure 10. Comparison between the experimental deposit obtained with fine gravel and a layer of 1 cm of water (a) and a chalk flow which collapsed onto shallow water (b).

Figure 11. Numerical results for a 2D model for a granular mass hitting a shallow water layer at a late phase of spreading. a) materials at contact (green: granular mass; blue: shallow water layer); b) velocity field at the same time step as a). Hydroplaning of the granular mass is simulated as resulting by 2D conditions and an impermeable flowing material.

3. Comparison with field data

Let us now compare in more detail the results for the ratio H/L as from our experiments with real field data for rock avalanches. Fig. 12 shows the results of the experiments and rock avalanche data on the...
same plot, together with the results of the simple analytical equation $H/L = \tan \alpha = 0.618 \theta + 9.8$. Note that the real data fall in two regions: rock avalanches occupy the lowermost region of the graph. Some data about the nearly-vertical collapse of large masses in the Yosemite valley are presented in the literature by Wieczorek et al. (1999), and Stock and Uhrhammer (2010), and these plot in the same area of a selection of chalk cliff collapses (Hutchinson, 2002; Duperret et al., 2006). They exhibit a much higher value of $H/L$. Data of our experiments fall in the region between these two data sets, above the data for real large rock avalanches and to the left of data for vertical cliff collapses. Many rock avalanches of small to medium size show a behavior similar to that of the experiments (e.g., rock avalanches just to the left of the experimental data, Fig. 12). We suggest a continuity of the data regions and, despite the differences in scale, material, and environment, a similarity between these different granular flows. The obvious differences between all these sets of data are summarized here. Our experimental flows are dry, while chalk collapses are wet; rock avalanches are mostly dry, but the fall on the alluvial plain can certainly wets their basal layers. Fragmentation of the granular mass is absent in the experiments given the low impact energy, but might alter the propagation of a real rock avalanche (McSaveney and Davies, 2007; Bowman, 2013), especially in correspondence of the slope break (De Blasio and Crosta, 2015). Considering these differences, the fact that the data exhibits a continuity with experimental flows is remarkable.

Figure 12 also shows the prediction of the simple model introduced by Eq. 1. This model can explain the increase in the value of $H/L$ as a function of the slope, even though different parameters should be adopted for the three different data sets. Real data can be fitted with relatively low friction coefficient and a coefficient of restitution of the order 0.2-0.3. With such values, both data sets for rock avalanches and chalk flows are approximately fitted by one single curve. Remarkably, this implies that the sharp increase in the ratio $H/L$ for nearly vertical collapses is well predicted by this simple analysis without invoking any material property of the material (chalk or granite for the Yosemite collapse).

Experimental data, however, require higher values of the friction coefficient, like the one measured in the laboratory. Following a modified version of the $\alpha\beta$-model by Lied and Bakkehoi (1980) for snow avalanches, we seek a correlation between the angle of slope $\theta$ and the angle of Fahrboschung $\alpha = \tan^{-1}(H/L)$ in the form $\alpha = K \theta + B$, where $K$ and $B$ are fitting constants. This empirical formula, shown in Fig. 12 with a thick dashed line, appears to fit rather well our data. Here the fitting coefficients for the experiments are much different from those found to range between 0.77 and 0.94 for snow avalanches (McClung, 2001). This is not surprising considering the complexity of snow avalanches in terms of wetting, cohesion, and air entrainment. However, the analysis shows that the origin for the increase of $H/L$ with slope angle has a common origin.
Another interesting feature observed in the experiments is the presence of a depression or groove left behind the deposit at the base of the inclined slope.

![Figure 12](image-url)

**Figure 12.** Ratio $H/L$ measured for lab experiments presented in this contribution and for real rock and snow avalanches and chalk flows gathered in the same figure. Curves represent the results of the proposed model considering the transfer of vertical to horizontal momentum for two different coefficients of friction and 3 values of restitution coefficient (0, 0.2, 0.3)

This is sometimes associated to the detachment of the deposit from the inclined slope because of the long runout and is commonly observed in case of low basal friction on the horizontal sector of the path. In presence of a basal erodible layer, a depression in correspondence of the slope toe is clearly associated with the erosion of part of the basal layer by the highly energetic flow and the forward prograding deposition for steep slopes. In the other cases a backward propagating shock wave covers the slope toe. Similar structures have been described by other authors analyzing flows from steep slopes. For example, Hutchinson (2002) describes impact hollows formed by the debris of chalk falls just out from the cliff foot, where fall deposits continue in long tongue like flows, but he does not provide an explanation for the phenomenon. Similar structures have been described (Smith et al., 1994, Fitzharris and Owens, 1984 and Owen et al., 2006) at the toe of steep slopes affected by snow avalanches and Corner (1980) introduced three types of impact-associated depressions. He suggests
that with increasing energy, impact tongues may acquire the shape of pits, and then of pools for the most energetic impacts. Corner (1980) also observes the strong erosion in the proximal slope toe sector, the striking similarity between the eroded volume and the frontal curved ridge deposit, and suggests the role of the abrupt change in slope as the main controlling factor for the emergence of such features.

4. Conclusions

This paper presents the results of experiments where a granular mass released along a slope reaches a horizontal plate. In some of the experiments, the plate is devoid of any granular medium. In this case, we find that the presence of a break of slope along the topography affects the run-out of the rock avalanche. The slope break is particularly important in this respect, as it will cause a loss of momentum perpendicular to the basal layer. Numerical and physical experiments show increased run-out when the slope break is smoothened, so confirming the importance of the slope break (Manzella and Labiouse, 2013; Manzella et al., 2013).

The novelty of the present work lays in the study of the interaction of the granular flow with an erodible layer resting on the horizontal plate, or with a thin water layer. In the first case, the formation of a granular wave controlling the erosion of the basal layer and the subsequent flow propagation, modes of accretion, and the final geometry of the deposit were observed in relation to the slope angle and the momentum of the flow. In general, the presence of an erodible dry layer hinders (if not in metastable conditions or close to instability) the further flow of the granular mass, but increases its size. Thus, the experiments provide indications that a granular flow falling onto a loose and dry erodible layer will generally decrease its speed and run-out in a real landslide, at least when an abrupt slope change exists. The physical reason is related to the fact that upon erosion the rock avalanche needs to transfer momentum to the erodible layer, which causes a speed decrease.

Numerical simulations by a FEM-ALE (arbitrary lagrangian-eulerian) code reproduce extremely well the dynamics observed both in time and space, including the erosion of the basal layer and geometry of the final deposit. This suggests that numerical modelling alone could be used to further investigate these events especially when beyond the reach of analogical experiments, for example at larger scale. Experiments with sand flows onto a thin water layer show that the sand may hydroplane, travelling for some distance detached from the base and that the front may detach from the body, all features shown also by numerical simulations and consistent with the field data.
We conjecture that when the basal layer is composed of a wet rather than dry medium, a lubrication effect may occur. Similarly, landslides falling onto glaciers are accompanied by a melting of ice and entrainment of water with a net increase in mobility (Schneider et al., 2011; Sosio et al., 2012; De Blasio, 2014). The gain of mobility due to lubrication may thus compensate or even outdo the effect of the momentum transfer. Similarly, a fall into a cohesive medium with non-Newtonian rheological properties such as alluvial muds may result in a strong lubrication depending on the yield strength of the bed material. It would be important to perform experiment with a wet layer with variable percentage of mud from pure water to dense mud.

Acknowledgements
The research was supported by PRIN Project: Time - Space prediction of high impact Landslides under changing precipitation regimes.

Appendix: Details on the numerical modeling
Following previous experience by the authors (Crosta et al., 2005; 2006, 2008, 2009, 2013a, 2013b, 2015) in simulating both small and large scale granular flows with different characteristics, the same FEM numerical approach (Crosta et al., 2009; Roddeman, 2013) has been applied to the problem presented in this paper. Because of the large displacements and deformations occurring within the material, a Lagrangian finite element method would be subjected to high mesh distortion and inaccuracy. The adopted approach, presented in Roddeman (2013) and Crosta et al. (2009, 2015) is a combined Eulerian-Lagrangian method which does not distort the FE mesh and demonstrated to guarantee accurate calculation results. We assume an elasto-plastic behavior with a standard Mohr-Coulomb yield law but other constitutive laws are available. The adopted isoparametric finite elements are 3-noded triangles in two dimensional simulations and eight-noded hexahedrals in three dimensions.

The initial equilibrium stress state for the granular mass contained in the releasing box is reached through quasi-static time stepping so that no inertial effect is introduced. Then gravity is incrementally applied in successive time steps. The release is simulated by deleting a containing wall so initiating the mass movement. The dynamic equilibrium equations are then solved for the entire area of the spreading material and without controlling conditions both for the onset and the evolution of the material erosion and deposition.

3. References
[1] Chen, H., Crosta, G. B., Lee C.F. (2006) Erosional effects on runout of fast landslides,
debris flows and avalanches: a numerical investigation. Geotechnique, 56, 5, 305–322.

[2] Choffat, P. (1929), L’ecroulement d’Arvel (Villeneuve) de 1922, Bull. Soc. Vaudoise Sci. Nat., 57(1), 5 – 28.

[3] Corner, G. D., (1980) Avalanche impact landforms in Troms, north Norway. Geografiska Annaler, 62A: 1-10

[4] De Blasio, F.V. (2014) Friction and dynamics of rock avalanches travelling on glaciers. Geomorphology 213, 88-98.

[5] De Blasio, F.V., Crosta G.B., (2015) The effect of slope geometry on rock avalanche fragmentation. submitted

[6] Crosta G.B., S. Imposimato, Roddeman, D.G. (2006) Continuum numerical modelling of flow-like landslides. Landslides from massive rock slope failure, Evans, S.G., Scarascia Mugnozza, G., Strom, A., Hermanns, R., (eds) NATO Science Series, Earth and Environmental Sciences, 49, 211-232

[7] Crosta, G. B., Imposimato, S., Roddeman, D.G., (2009) Numerical modeling of 2-D granular step collapse on erodible and nonerodible surface. J. Geophys. Res., 114, F03020.

[8] Crosta, G. B., S. Imposimato, D. Roddeman, S. Chiesa, Moia, F. (2005), Small fast moving flow-like landslides in volcanic deposits: The 2001 Las Colinas Landslide (El Salvador), Eng. Geol. Amsterdam, 79(3–4), 185–214, doi:10.1016/j.enggeo.2005.01.014.

[9] Crosta, G.B., Imposimato, S., Roddeman, D.G. (2008) Numerical modelling of entrainment/deposition in rock and debris-avalanches. Eng. Geology, 109, 1-2, 135-145.

[10] Crosta, G.B., Imposimato, S., Roddeman, D. (2013a) Interaction of Landslide Mass and Water Resulting in Impulse Waves. In Landslide Science and Practice, Vol. 5: Complex Environment. Margottini, C., Canuti, P., Sassa, K. (Eds), ISBN 978-3-642-31426-1,28 DOI 10.1007/978-3-642-31427-8, Springer, 49-56

[11] Crosta, G.B., Imposimato, S., Roddeman, D., Frattini, P. (2013b) On Controls of Flow-Like Landslide Evolution by an Erodible Layer. In Landslide Science and Practice, Vol. 3: Spatial Analysis and Modelling. Margottini, C., Canuti, P., Sassa, K. (Eds), ISBN 978-3-642-31426-1,28 DOI 10.1007/978-3-642-31427-8, Springer, 263-270

[12] Crosta, Hermanns, R.L.; Valbuzzi, E., Frattini, P., Valagussa, A. (2014) Large slope instabilities in Northern Chile and Southern Peru. Geophysical Research Abstracts,
[13] Cruden, D.M., Hungr, O. 1986. The debris of Frank slide and theories of rockslide-avalanche mobility. Canadian Journal of Earth Sciences, 23, 425-432.

[14] Denlinger, R. P., Iverson R. M. (2001), Flow of variably fluidized granular masses across three-dimensional terrain: 2. Numerical predictions and experimental tests, J. Geophys. Res., 106(B1), 553 – 566, doi:10.1029/2000JB900330.

[15] Dufresne A., (2012) Granular flow experiments on the interaction with stationary runout path materials and comparison to rock avalanche events. Earth Surf. Processes Landforms, 37, 1527-1541

[16] Duperret, A., Genter, A., Martinez, A., Mortimore, R.N. (2006) Coastal chalk cliff instability in NW France: role of lithology, fracture pattern and rainfall. In Mortimore, R. N. and Duperret, A. (eds), Coastal Chalk Cliff Instability. Geological Society, London, Engineering Geology Special Publications, The Geological Society of London 20, 33-55.

[17] Fitzharris, B. B., Owens, I. F., (1984) Avalanche tarns. Journal of Glaciology, 30(106): 308-312.

[18] Forterre, Y., O. Pouliquen (2008), Flows of dense granular media, Annu. Rev. Fluid Mech., 40, 1–24.

[19] Gray, J. M. N. T. Wieland, M., Hutter K. (1999) Gravity-driven free surface flow of granular avalanches over complex basal topography. Proc. R. Soc. Lond., A, 455, doi: 10.1098/rspa.1999.0383 Günther, A., and Thiel, C. (2009). Combined rock slope stability and shallow landslide susceptibility assessment of the Jasmund cliff area (Rügen Island, Germany). Nat. Hazards Earth Syst. Sci., 9, 687–698, 2009

[20] Hakonardottir, K. M., Hogg, A. J., Johannesson, T., Kern, M., Tiefenbacher, F. (2003a). Large scale avalanche braking mound and catching dam experiments with snow. A study of the airborne jet. Surveys in Geophysics, 24, 543–554.

[21] Hakonardottir, K. M., Hogg, A. J., Johannesson, T., Tomasson, G.G. (2003b) A laboratory study of the retarding effects of braking mounds on snow avalanches. Journal of Glaciology, 49(165), 191–200.

[22] Hewitt, K. (2006) Rock avalanches with complex run out and emplacement, Karakoram Himalaya, Inner Asia. S.G. Evans et al. (eds.), Landslides from Massive Rock Slope Failure, Springer. Printed in the Netherlands 521–550.

[23] Hungr O, Evans SG. (2004) Entrainment of debris in rock avalanches; an analysis of a long run-out mechanism. Geol. Society of America Bulletin 116(9–10): 1240–1252.
[24] Hutchinson, J.N. (2002) Chalk flows from the coastal cliffs of northwest Europe. Geological Society of America, Reviews in Engineering Geology, 2002, 15, 257-302Ilstad, T. De Blasio, F.V., Elverhøi, A., Harbitz, CB, Engvik, L., Longva, O. and Marr, J. (2004). On the frontal dynamics and morphology of submarine debris flows. Marine Geology. 213, 481-497.

[25] Jaboyedoff, M. (2003), The rockslide of Arvel caused by human activity (Villeneuve, Switzerland): Summary, partial reinterpretation and comments of the work of Ph. Choffat (1929): L’ecroulement d’Arvel (Villeneuve) de 1922. Bull. SVSN 57, 5 – 28, Open File Rep. 3, Int. Indep. Cent. of Clim. Change Impact on Nat. Risk Anal. in Mt. Areas, Lausanne, Switzerland. (Available at http://www.quanterra.org/erosionhazard.htm.)

[26] Lacaze, L., J. C. Phillips, Kerswell, R. R. (2008), Planar collapse of a granular column: Experiments and discrete element simulations, Phys. Fluids, 20, 063302.1–063302.12, doi:10.1063/1.2929375.

[27] Lajeunesse, E., A. Mangeney-Castelnau, Villette, J.P. (2004), Spreading of a granular mass on a horizontal plane, Phys. Fluids, 16, 2371–2381, doi:10.1063/1.1736611.

[28] Lajeunesse, E., J. B. Monnier, Homsy, G.M. (2005), Granular slumping on a horizontal surface, Phys. Fluids, 17, 103302.1 – 103302.15, doi:10.1063/1.2087687.

[29] Legros, F. (2002) The mobility of long-runout landsides, Engineering Geology, 63, 301-331.

[30] Lied, K., and S. Bakkehoi (1980). Empirical calculations of snow-avalanche run-out distance based on topographic parameters. J. Glac. 26, 165-177.

[31] Liestol, O., (1974) Avalanche plunge pool effect. Norsk Polarinstuttt Arbok 1972, 179-181.

[32] Lube, G., H. Huppert, S. Sparks, and A. Freundt (2005), Collapses of two dimensional granular columns. Phys. Rev. E, 72, 041301.1–041301.10, doi:10.1103/PhysRevE.72.041301.

[33] Lucchitta, B. K. (1979), Landslides in Valles Marineris, Mars, J. Geophys. Res., 84(B14), 8097–8113, doi:10.1029/JB084iB14p08097.

[34] Ma, A.,Liao, H., Ning, C., Feng, Z. (2014) Stability analysis of a high slope along a loess plateau based on field investigation and numerical analysis. K. Sassa et al., (eds), Landslide Science for a safer Geoenvironment, Springer, vol. 1, 451-458

[35] Mangeney, A., L. S. Tsimring, D. Volkson, I. S. Aranson, and B. Bouchut (2007), Avalanche mobility induced by the presence of an erodible bed and associated
entainment, Geophys. Res. Lett., 34, L22401,

[36] Manzella, I., Einstein, H. H., Grasselli, G. (2013). DEM and FEM DEM modelling of granular flows to investigate large debris avalanche propagation. In: C. Margottini et al. (Eds.). Landslide Science and Practice, Vol. 3. Springer Verlag, Berlin-Heidelberg, 247-253.

[37] Manzella, I., Labiouse, V. (2013). Empirical and analytical analyses of laboratory granular flows to investigate rock avalanche propagation. Landslides (2013) 10:23–36, DOI 10.1007/s10346-011-0313-5

[38] Manzella, I., Labiouse, V. (2008a): Qualitative analysis of rock avalanches propagation by means of physical modelling of not constrained gravel flows. Rock Mechanics and Rock Engineering, 41 (1), 133–151

[39] McClung, D.M. (2001) Extreme avalanche runout: a comparison of empirical models. Can. Geotech. J. 38: 1254–1265, DOI: 10.1139/cgj-38-6-1254

[40] McConnell, R.G. and Brock, R.W., (1904). Report on great landslide at Frank, Alberta, Canada. Can. Dep. Inter., Annu. Rep., 1902—1903, Part 8, 17 pp.

[41] McDougall, S. (2006) A new continuum dynamic model for the analysis of extremely rapid landslide motion across complex 3D terrain. PhD thesis, Univ British Columbia, 253 pp.

[42] McSaveney MJ, Davies TRH, Hodgson KA (2000) A contrast in deposit style and process between large and small rock avalanches. In: Bromhead E, Dixon D, Ibsen M–L (eds) Landslides in research, theory and practice. Thomas Telford Publishing, London, pp 1053–1058

[43] McSaveney, M.J., Davies, T. (2007) Rockslides and their motion. In Sassa K., Fukuoka F., Wang F., Wang G. (eds), Progress in landslide science, Springer, Berlin, 113-133

[44] Mohrig, D., Ellis, C., Parker, G., Whipple, K.X., and Hondzo, M. (1998). Hydroplaning of submarine debris flows. GSA Bulletin 110, 387-394.

[45] Owen, G., Matthews, J. A., Shakesby, R. A., He, X. (2006), Snow-avalanche impact landforms, deposits and effects at Urdvatnet, southern Norway: implications for avalanche style and process. Geografiska Annaler: Series A, Physical Geography, 88: 295–307. doi: 10.1111/j.0435-3676.2006.00302.x

[46] Post, A. (1967) Effects of the March 1964 Alaska Earthquake on Glaciers. USGS Professional Paper 544–D, 54 p.

[47] Pudasaini, S., Kroner, C. (2008). Shock waves in rapid flows of dense granular
materials: Theoretical predictions and experimental results. Phys. Rev. E 78, 041308.

[48] Pudasaini, S.P., Hutter, K. (2006). Avalanche Dynamics: Dynamics of Rapid Flows of Dense Granular Avalanches., ISBN: 3-540-32686-3, Springer-Verlag, 602 pp.

[49] Roddeman, D.G. (2011), TOCHNOG user’s manual. FEAT, 255 pp, www.feat.nl/manuals/user/user.html.

[50] Scheidegger, A.E. 1973. On the prediction of the reach and velocity of catastrophic landslides. Rock Mechanics 5, 231-236.

[51] Schneider, D., Huggel, C., Haeberli, W. and Kaitna, R. (2011). Unraveling driving factors for large rock–ice avalanche mobility. Earth Surf. Process. Landforms, 36: 1948–1966. doi: 10.1002/esp.2218

[52] Smith, D.J., McCarthy, D.P., Luckman, B.H. (1994) Snow-Avalanche Impact Pools in the Canadian Rocky Mountains Arctic and Alpine Research, Vol. 26, No. 2, 1994, pp. 116-127

[53] Sosio, R., Crosta, G., & Hungr, O. (2008). Complete dynamic modeling calibration for the Thurwieser rock avalanche (Italian Central Alps). Engineering Geology, 100(1-2), 11-26.

[54] Sosio, R., Crosta, G.B., Hungr, O. (2011) Numerical modeling of debris avalanche propagation from collapse of volcanic edifices. Landslides, DOI: 10.1007/s10346-011-0302-8.

[55] Sosio, R., Crosta, G.B, Chen, J.H, Hungr, O. (2012) Modelling rock avalanche propagation onto glaciers. Quaternary Science Reviews (Impact Factor: 4.08). 07/2012; 47:23-40. DOI:10.1016/j.quascirev.2012.05.010

[56] Stock, G. M. and Uhrhammer, R. A. (2010), Catastrophic rock avalanche 3600 years BP from El Capitan, Yosemite Valley, California. Earth Surf. Process. Landforms, 35: 941–951. doi: 10.1002/esp.1982

[57] Strom, A. (2006) Morphology and internal structure of rockslides and rock avalanches: grounds and constraints for their modelling. S.G. Evans et al. (eds.), Landslides from Massive Rock Slope Failure, Springer, 305–326.

[58] von Poschinger, A., Kippel, Th (2009) Alluvial deposits liquefied by the Flims rock slide. Engineering Geology, Vol. 103, 1, 50-56.

[59] Wieczorek GF, Morrissey MM, Iovine G, Godt J. 1999. Rock-fall potential in the Yosemite Valley, California. US Geological Survey Open-file Report 99–578.Yugsi Molina, F. X., Hermanns, R. L., Crosta, G. B., Dehls, J., Sosio, R., Sepúlveda, S.A.
Geomorphological analysis, monitoring and modeling of large rock avalanches in northern Chile (Iquique area) for regional hazard assessment. Geophysical Research Abstracts, Vol. 14, EGU2012-8925, 2012