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MONITORING AND MODELLING OF ROCK SLIDES AND ROCK AVALANCHES

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ABSTRACT

Rockslides can appear in a large variety of types and with different characters which make difficult their understanding and the prediction of their behaviour. This contribution highlights some of the most important steps in rockslide monitoring and modeling showing the relationships between them. Monitoring is a fundamental step in the understanding of such phenomena. The analysis of the possible types of failure and collapse are extremely important especially when a rapid acceleration, a successive transformation in a rock avalanche and a long runout are foreseen. Some examples of ground surface and subsurface rockslide displacements are shown and analysed with respect to the possible definition of thresholds. In case of a sudden collapse and long runouts erosion and impact against water reservoirs should be considered and this can be performed through different approaches. Some results of laboratory tests, two dimensional and three dimensional rockslide-rock avalanche numerical models are presented and tested against some case studies, together with the interaction with water reservoirs.

Key words: *rockslide, monitoring, slow to fast movement, collapse, warning thresholds, rock avalanche, modeling, erosion, impulse wave*

INTRODUCTION

Rockslides occur along valley flanks in different positions, affecting them for their entire length or at specific sectors, and as isolated phenomena or within larger slope instabilities. Depending on the rock mass properties, the type of instability, local slope geometry and the triggering conditions these phenomena can evolve into rock avalanches posing extraordinary risks where morphological conditions and valuable elements occur. Therefore understanding rockslide behaviour and possible evolution is an important step to be accomplished for both hazard and risk assessment, as well as for civil protection and emergency actions.

As stated above, evolution of these phenomena is controlled by slope morphology and its changes, and by lithological, structural, geomechanical, hydrological and meteo-climatic factors. These slope instabilities evolved over a timescale of thousands of years, characterized by phases of different activity and geomorphological evolution, including loading and unloading cycles, toe erosion, incision by running waters, creep-like movement or long resting phases interrupted by periodical reactivations, which in some cases can evolve in catastrophic collapses. During such long time intervals the rock mass properties can change because of water seepage, weathering, disturbance and dislodging, as well as progressive damaging. The progressive accumulation of displacement can cause a gradual change in fracture intensity, opening, and weathering with direct consequences on rock mass strength and permeability, and controlling the sensitivity to external perturbations (e.g. rainfall, snowmelt, seismic shaking). In particular, snow melting and heavy rainfall are the most common triggers of annually recorded displacements in alpine rockslides. Shear zones at the base of rockslides can evolve from intensely fractured and blocky to very fine grained. This will cause a progressive localization, decrease in strength and in permeability, with consequences on sensitivity to groundwater level changes and with recorded displacement for comparable triggering events.

As a consequence, rockslide state of activity can change in time following a seasonal trend, with acceleration and deceleration behaviour depending both on internal and external controlling factors.

Furthermore, rockslides can affect very large volumes of rock mass which through time can undergo differential degree of damaging. Then, rockslides can show a mix of different behaviours within their boundaries, being composed by sectors formed by very different materials (i.e. lithology, loose coarse or fine debris, dismembered or sound rock mass, faulted or folded rocks) and characterized by different geometry (e.g. steep rock scarps, flat or even back tilted head, steep slide toe). This complexity makes intrinsically difficult the interpretation of the slope movements because of both the different type of instability and the relative disturbance between the different types of movement (e.g. superficial movements masking deeper ones).

These conditions differentiate most of the natural slope instabilities from those along artificial excavations. At the same time, they strongly affect the possible monitoring strategy to be applied at each site, in terms of type and frequency of monitoring, as well as the modelling approach. The fact that most of the natural slopes can reflect a long time evolution makes then more difficult to extrapolate the initial slope conditions as well as the precise evolutionary step at which a specific landslide is examined. The temporal pattern of displacement, the state of activity (i.e. active, reactivated, suspended, intermittent) and the evolutionary trend of a landslide (slow vs. catastrophic, continuous vs. episodic) depend on the geomorphological history, the extent of the monitoring time window, the local morphology or degrees of freedom (Broadbent & Zavodni, 1982). Long periods of inactivity or minor movements (difficult to be recognized in absence of a monitoring network) as well as availability or incompleteness of monitoring data series make the understanding prohibitive. Indeed, the analysis of long monitoring time series, of the trend and possible evolution of landslide activity gives the opportunity to define threshold values for pre-failure, failure and post-failure phases to be adopted in landslide monitoring, early warning and risk management.

Therefore, a sound understanding of the future evolution of a rockslide and its proneness to catastrophic collapse requires the availability of monitoring data. Monitoring techniques are undergoing an extremely rapid evolution and are providing a huge amount of information to be treated and analysed. Traditional point-like monitoring activities are progressively replaced by modern more spatially distributed approaches. Point-like data can result insufficient or misleading in the interpretation, being representative of local behaviour, and are sometimes hindered by logistic and technical difficulties. Spatially-distributed data (e.g. laser scanning surveys, radar interferometry) can be suitable for general understanding and for early warning scopes, providing a way to by-pass network implementation and maintenance problems. The same can be said for subsurface ground monitoring due to the availability of continuous and real-time measurements of displacement, pore pressure or piezometric head along vertical profiles which can be coupled to advanced geophysical surveys.

Finally, spatially-distributed and almost continuous monitoring time series allow a more complete calibration of numerical models as well as the development of more advanced or suitable mechanical models and constitutive laws. This finally results in a more advanced predictive capability in terms of definition of the failure surface geometry, unstable volume, expected reaction to external perturbation and in supporting collapse and then runout modelling (i.e. by providing volume, geometry, water content data).

From all these points of view, the Vajont rockslide provides an incredible field laboratory because of the amount of collected information both before and after the landslide, till to our times, the number of developed models, the performed laboratory tests and the availability of monitoring data. At the same time, the terrible consequences in terms of loss of human lives, together with the complexity of the phenomenon, in terms of time evolution, the fast runout and the involvement of the water reservoir make of this rockslide an extremely complex phenomenon also for what concerns the development of methods for a more quantitative hazard and risk assessment.

EARLY WARNING THRESHOLDS

Early Warning Systems (EWS) requires the definition of thresholds values for parameters and/or indicators for which a substantial change in system behaviour can be observed and a series of action can be undertaken.

Even when good quality monitoring data (i.e. continuous, spatially distributed, real time) are available, prediction or forecasting a slope failure and collapse in time is a difficult task. This is especially true when the involved rockslides are sensitive to external perturbations, and physics-based thresholds for some suitable monitored variables are extremely sensitive to changes or are under continuous evolution. At the same time, for long-lived rockslides, it is sometimes difficult to define the instant of initial failure or change in behaviour, together with the most significant points/areas to be monitored, the successive rate of displacement and the correlations with specific triggering events. Furthermore, as above mentioned these landslides are often characterised by complex geometry and geology making difficult a robust geomechanical characterization and a reliable quantitative modelling.

Several empirical/phenomenological approaches based on the "slope creep" theory (Saito & Uezawa, 1961; Fukuzono, 1985; Voight, 1988; Crosta *et alii*, 1999; Crosta & Agliardi, 2002; Rose & Hungr, 2007) have been suggested to forecast slope failures by the analysis of time series of monitoring data. Inverse velocity methods, based on inverse velocity vs time plots, are based on empirical observations, which can agree with damage theory and can be a useful tool for deciding about early warning management and civil protection actions. The same methods can be used under some specific conditions to verify the effectiveness of stabilizing actions (see Rose and Hungr, 2007) under constant perturbations. At the same time they do not offer a clear understanding of the rockslide evolution for more complex scenarios.

These models about accelerating trends have been reconsidered (Petley *et alii*, 2002; Amitrano, 2005; Amitrano & Helmstetter, 2006; Faillettaz *et alii,* 2010) trying to understand the processes which lead to a rupture and its propagation through a material or a slope up to a possible final collapse. Unfortunately, when forecasting a possible collapse a series of unknowns and uncertainties remain relative to the antecedent landslide or slope behaviour, sensitivity to perturbations, changes in material properties and level of perturbation. Crosta & Agliardi (2003) propose a methodology to obtain physics-based alert velocity thresholds for landslides with complex kinematics and sensitivity to external triggers. The method, based on the non-linear Fukuzono-Voight relationship (Voight, 1988) between acceleration and displacement rate, uses monitoring data to define thresholds. Non-linear fitting allows to derive values for model parameters which can be considered typical of the state and properties of the physical system evolving towards failure. Synthetic velocity vs time curves can be generated providing a basis to quantitatively establish alert velocity threshold values at different time intervals before the expected failure.

To illustrate the problems and possibilities associated to rockslide monitoring and modelling we start from a series of case studies. These case studies are not represented into detail but are brought as examples of behavior and of possible consequences in modelling.

ROCKSLIDE MONITORING

As above mentioned, rockslides can evolve in rapid and long runout phenomena, along some specific shear zones and with changes in rock mass properties. This requires a well designed monitoring network both for the movement characterization and for the setting up and management of an EWS. The general design of a monitoring network is not the focus of this manuscript, whereas the idea is just to show some special features observed as some specific case study.

Localised subsurface displacement has been observed at different rockslide sites but its occurrence in time is not generally available at least on very short time scales. Indeed, the temporal distribution is extremely important to evaluate the delay time between perturbation and displacement, the sensitivity to the perturbations, the way of accumulating displacement, the possibility to generate alert signals in quasi real time. The Mt de La Saxe rockslide is a complex instability for which a relatively complete dataset is available. The time series of displacement through a specific accelerating event is here presented.

Some of the boreholes drilled within the rockslide and crossing the deep failure surface have been equipped with some multi-parametric columns (DMS by CSG) with measuring elements 1 m in length and with a high resolution and a continuous recording capability.

Figure 1 shows an example of displacement records measured at different depth along two different boreholes during a two weeks interval. These plots show some interesting trends in the occurrence and distribution of deep seated displacements. In particular, they seem to occur:

- in a continuous-like mode;
- in a step-like mode;

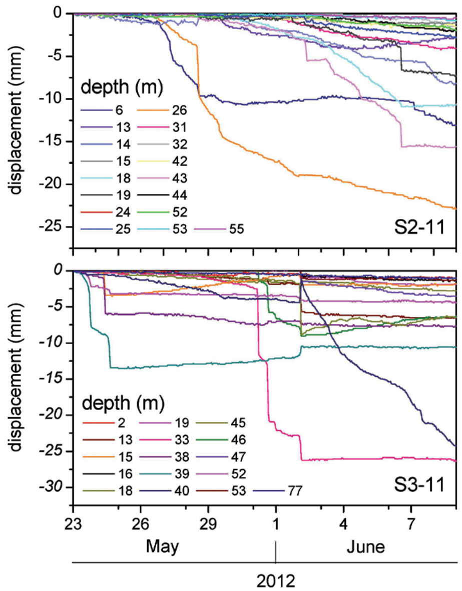

Fig. 1 - Plots of hourly recordeddisplacements measured at different depth (seelegend) during a reactivation event (May –June 2012) by two multi-parametric DMS columns at the La Saxe rockslide

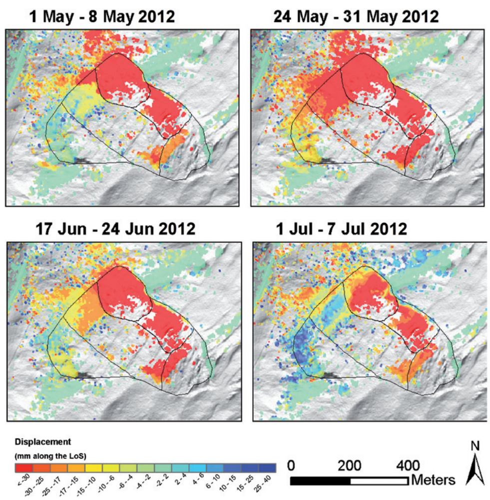

Fig. 2 - GB-InSAR maps of ground surface displacement (May-July 2012) for the La Saxe rockslide

- with progressive acceleration and decelerations, associated to each of the two previous modes.

This figure shows displacements at some specific intervals, as recorded by the instrumentation, which could suggest different mechanisms for their occurrence: a stick slip behavior along the failure surface, with stress accumulating progressively, or a progressive increase in water pressure along the closed shear zone till the effective stress limit is reached for shearing to occur. The successive pressure dissipation during the opening or dilation of the shear zone can cause an increase in the effective stress and the arrest of displacement.

These displacements are reduced with respect to the larger ground surface displacements (see map of displacements, Fig. 2 and the time histories at some points in Fig. 3, upper inset), measured by a LisaLab Ellegi GB-InSAR and total station (lower inset in Fig.

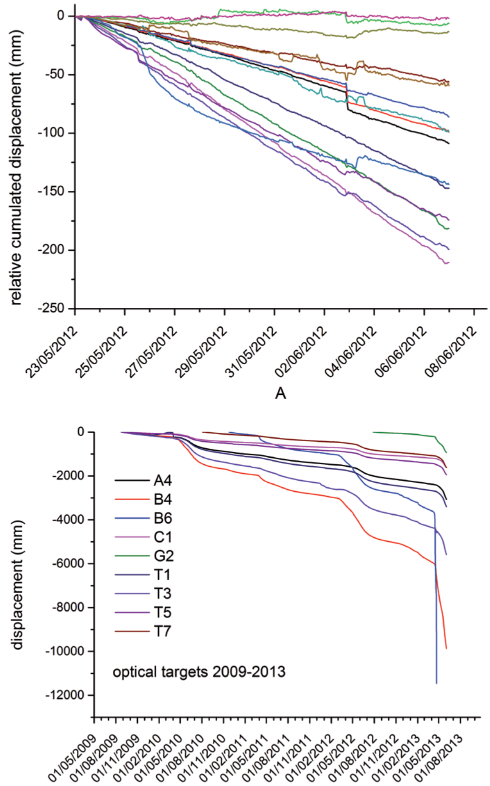

Fig. 3 - Recorded ground surface displacements measured: upper figure) by the LisaLAB – ELLEGIGB-InSAR in the same period (May-June 2012,average time interval 4 hrs) as in Figure 1, andlower figure) by a total station (daily displacement)at different points during the 2009-2013 interval atthe La Saxe rockslide

3), which accumulate also the effects of the presence of soil cover, local topographic gradient and its changes.

At the same time, ground surface displacement maps allow for rockslide zoning according to the different state of activity (see black lines in Fig. 2).

The different resolution of the instruments and the acquisition time adopted for the different type of instrumentation can explain some of the discrepancies and the possibility to recognize the same behavior at the ground surface and at depth. This stress both the relevance of continuous monitoring and the resolution of the adopted instrumentation in the understanding of mechanisms.

Figure 3 shows also some other important aspects, namely: the seasonal accelerations/reactivation, the change in seasonal behavior between different years, the presence of other episodes out of the more regular seasonal behavior, the possibility to have exceptional accelerations (2013), the rapid initial acceleration and progressive deceleration, the continuous slow displacement in cold and dry periods.

This figure also resumes some of the difficulties at defining displacement rate thresholds on the basis of available data, or in absence of continuously recorded displacements. The 2013 acceleration shows an important increase in ground surface displacement rate, with respect to the previous year, with values larger than 100 mm d-1. These values, together with their rate of increase, are comparable with those relative to historical rockslides which underwent a catastrophic collapse. In general, the displacement rate just before failure varies within a large interval (Fig. 4), from a few mm per day to some thousands of mm per day, and this wide variability explains the difficulty in thresholding by means of comparison with historical records.

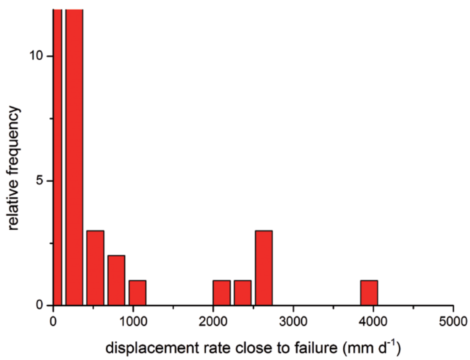

Fig. 4 Histogram of relative frequency of displacement rate values close to the catastrophic collapse for a sample of 53 historical events

ROCKSLIDE - ROCK AVALANCHE MODELING

Modeling the stability and evolution of rockslides implies the availability of geometrical, kinematical and mechanical data. Slope stability is controlled by many factor that can be introduced in one dimensional up to three dimensional analyses. Groundwater recharge and flow are the main controlling factors for seasonal acceleration at many rockslide sites. Nevertheless, the progressive accumulation of displacement and deformation causes a progressive change in properties, namely: the decrease in strength along the failure surface and the failing mass, the decrease in permeability along the shear zone, the increase in permeability within the rockslide mass. Therefore, a constant properties approach does not usually allow for a complete modeling of these phenomena and of their evolution in time.

The complete description of the possible modeling approaches is out of the scope of this manuscript, and in the following the possibility to model displacement trend in time and the evolution of rockslide into rock avalanche on erodible materials, and within water reservoirs will be considered.

EFFECTS OF ERODIBLE BASAL LAYER

Rapid collapse of a rock slide can cause a transformation into a rock-avalanche characterized by high velocity and mobility, variable material properties and entrainment capability. Entrainment (Crosta, 1992; McDougall, 2006; Hungr & Evans, 2004; Chen *et alii*, 2006; Crosta *et alii*, 2008a, b, Crosta *et alii*, 2013) causes an increase in volume, and a change in properties, function of the material fed to the flow (e.g. partially or fully saturated soil, rock, ice), which in turn influence the emplacement mechanisms and the runout. Changes in properties (e.g. thickness, physical mechanical properties and behaviour, frictional, cohesive, permeability), and behaviour of the erodible substrate material (e.g. collapsible, liquefiable, dilatant) control the quantity of material entrained, dragged, sheared, ploughed, bulldozed or unaffected by the landslide motion (e.g. Dufresne & Davies, 2009).

The influence of these factors on the evolution of a rock slide – rock avalanche can be studied by laboratory scale experimental tests (Figs 5 and 6) and numerical modelling. Results of some simple tests with motion of a dry granular material over an erodible horizontal bed have been performed.These tests demonstrate the role of slope angle, deposit thickness, material properties on the entrainment and the deformation of the erodible substrate as well the strong modification in the motion characteristics in time and space. Backward aggradation and progradation of the deposit are controlled by the change in slope and the geometrical constrains. The flow profile changes with time showing the progressive involvement of dynamic and static properties till a complete arrest.

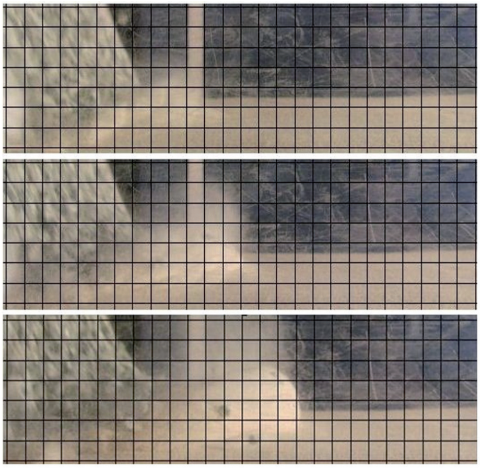

Fig. 5 - Physical model of the erosion process triggered by a coarse granular avalanche on a fine sand substrate

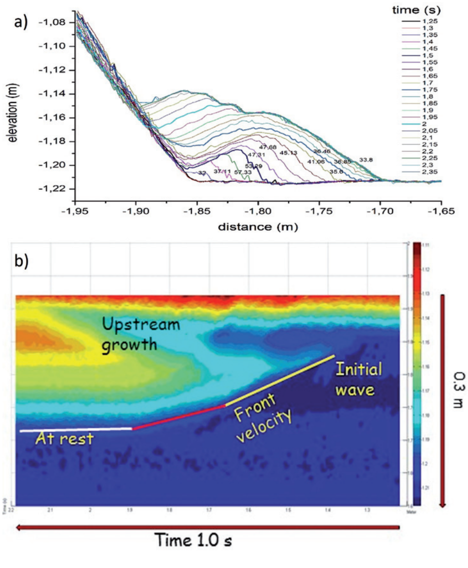

Fig. 6 - upper) Longitudinal profiles (time interval: 0.05 s) showing the evolution of the deposit in time; lower) plot of the change in profile height with time and description of the main features describing the granular avalanche (fine uniform sand) motion and deposition

2D and 3D numerical simulations can allow to study in depth the main physical and geometrical controlling factors. A series of fully 3D numerical analyses has been performed by using a Finite Element code (Roddeman, 2011; Crosta *et alii*, 2003, 2006, 2009) considering a Mohr-Coulomb substrate material from almost purely frictional to purely cohesive. Crosta *et alii* (2008a,b, 2009, 2013) used these together with different thicknesses for the substrate material to verify the effects.

Simulations (see example in Fig. 7) show that the thickness of the substrate is generally: inversely related to runout especially for weaker than avalanche materials; the deposit extent grows for decreasing material layers; very weak substrates cause larger spreading especially for thin layers; a radial deformation zone is developed; velocity and thickness of the entrained material increase with saturation; wedge like failures or folding can be observed in the substrate material.

WATER RESERVOIRS AND IMPULSE WAVES

Rockslides can originate within water reservoirs (artificial and natural, lakes, fjords) and rock avalanche

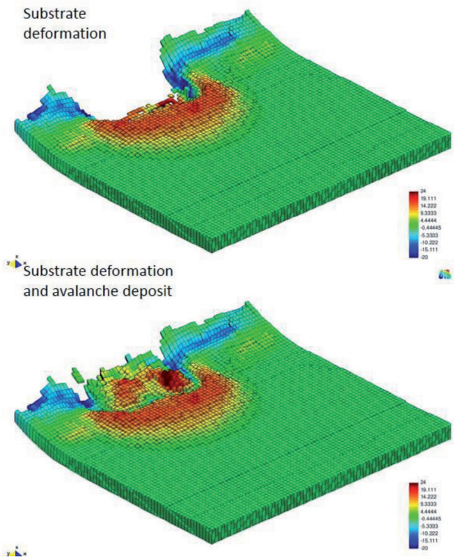

Fig. 7 - Fully 3D simulation of the avalanche/substrate interaction. upper) deformation accumulated by the substrate at the end of the avalanche motion; lower) as above but with the avalanche deposit in place

can reach them along their path impacting the immobile mass of water at high speed. This can originate large landslide generated impulse waves or landslide tsunami, generally subdivided in three stages: initiation, propagation and runup. As for the case of substrate entrainment the impulse wave is controlled by the landslide initial position (i.e. high on a slope, partial or comple tesubmergence of the toe) and speed, the type of material, the slope subaerial and subaqueous geometry, the relative size of the landslide mass with respect to the depth of water. Landslide impulse waves and tsunamis are characterized by larger height in the near field, rapid decay, high turbulence, flow separation and subsequent reattachment, strong mixing of air and water.

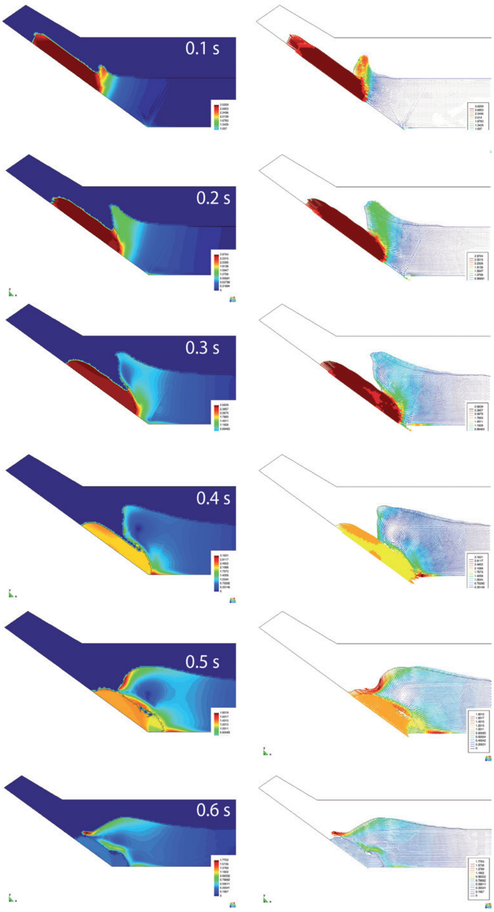

Fig. 8 - 2D modelling of Sælevik's et alii. (2009) experiment. Velocity field (m s-1, to the left) and velocity vectors (to the right) are shown. The impact velocity of a quasi-rigid 1 m long rockslide is 3.38 m s^{-1} (Landslide Froude number, Fr = 1.4). Impact and backward collapsing impact crater are very well simulated

A series of historical landslide tsunami events occurred as a consequence of subaerial landslides: the 1959 Pondesei (Italy) debris slump generating a 20 m high impulse wave; the 1963 Vajont rockslide (Italy, about 2900 casualties; Viparelli & Merla, 1968) characterised by a low water depth to landslide thickness ratio; the 1958 Lituya Bay event (Alaska, Miller, 1960, predated by other events on 1853-1854, 1936, 1958), the 1934 Tafjord event (Norway, Blikra *et alii*, 2005), the Loen events (Norway), and the volcano collapses in deep ocean waters (Hawaii and Canary islands, Keating & McGuire, 2000; Ward & Day, 2003).

Because of the intrinsic risk associated to these phenomena experimental tests on 2D and 3D wave generation and propagation have been completed (Kamphuis & Bowering, 1970; Huber, 1980; Müller, 1995; Huber & Hager, 1997; Fritz, 2002; Panizzo *et alii*, 2005; Heller, 2007; Heller& Kinnear, 2010; Sælevik *et alii*, 2009; Bosa & Petti, 2011), using both rigid blocks and deformable granular" masses. These tests resulted in the development of various analytical and numerical methods which in general consider subaerial movement and material properties in a simplified way (Harbitz, 1992; Jiang & LeBlond, 1993; Grilli et al., 2002; Grilli & Watts, 2005; Quecedo *et alii*, 2004; Lynett & Liu, 2005).

Based on the previous experiences a series of numerical simulations has been completed with the aim to simulate a continuous deformable landslide mass spreading along a slope, both under subaerial and submerged conditions, interacting with a water body. 2D experimental tests performed by Fritz (2002) and Sælevik *et alii* (2009) with deformable masses or rigid blocks, respectively, have been considered (Crosta *et alii*, 2013). In our FE analyses water is considered an inviscid almost incompressible fluid. Figure 8 shows the following sequence of steps for a semi-rigid rockslide mass: impact, progressive submergence of the mass accompanied by the water crater formation and successive backward collapse and closure, backward flow over the slide material, and finally splash rising along the sloping ground. Figure 9 shows the evolution of a granular avalanche elongating and thinning along the subaerial slope, and shortening after the impact with the development of a pronounced steep and convex snout front.

The avalanche front is torn off during subaqueous flow developing a transient backward tilted plume.

Crater collapse takes place when the material has reached the bottom of the water tank.Then a back flow to the shore and a large part of the flow generates a primary wave which propagates to the right along the tank.

2D and 3D slope stability analyses and runout simulations, the last ones without considering the presence of the water reservoir, have been performed by Crosta *et alii* (2007). Modeling has been performed using available geomechanical properties, whereas model calibration and validation have been accomplished by comparing the final rockslide geometry (profiles and 3D deposit geometry).

The next step in the analysis consisted in the 2D simulation of the Vajont rockslide and of the consequent wave performed (Crosta *et alii*, 2013) starting from the available topographic (maps and cross sections) and historical records of the events (Rossi & Semenza, 1965). The simulation (Fig. 10) well fits the observed phenomenon in terms of displacement, total duration, impact against the opposite valley flank, thrusting and deformation of the paleo-landslide material. The water wave overestimate the maximum wave runup and this is a primary effect of the fully 2D simulation, which preserves the water volume within the reservoir.

Because of this limitation a fully 3D rockslide-water reservoir simulation has been considered. For this model about 800.000 elements have been used to discretize the rockslide, the water reservoir and the dam. The rockslide was modelled as a Mohr-Coulomb material (ρ = 24 kN/m^3; ν = 0.23; E = 10^{10} Pa; ϕ = 23°, c = 100 kPa) and along the basal plane (ϕ = 7.5 to 5.7°; see Skempton, 1966; Hendron & Patton, 1985; Tika & Hutchinson, 1999; 8°-10° down to almost 0° for shear rates above 0.01 m s^{-1}, Ferri *et alii*, 2011),

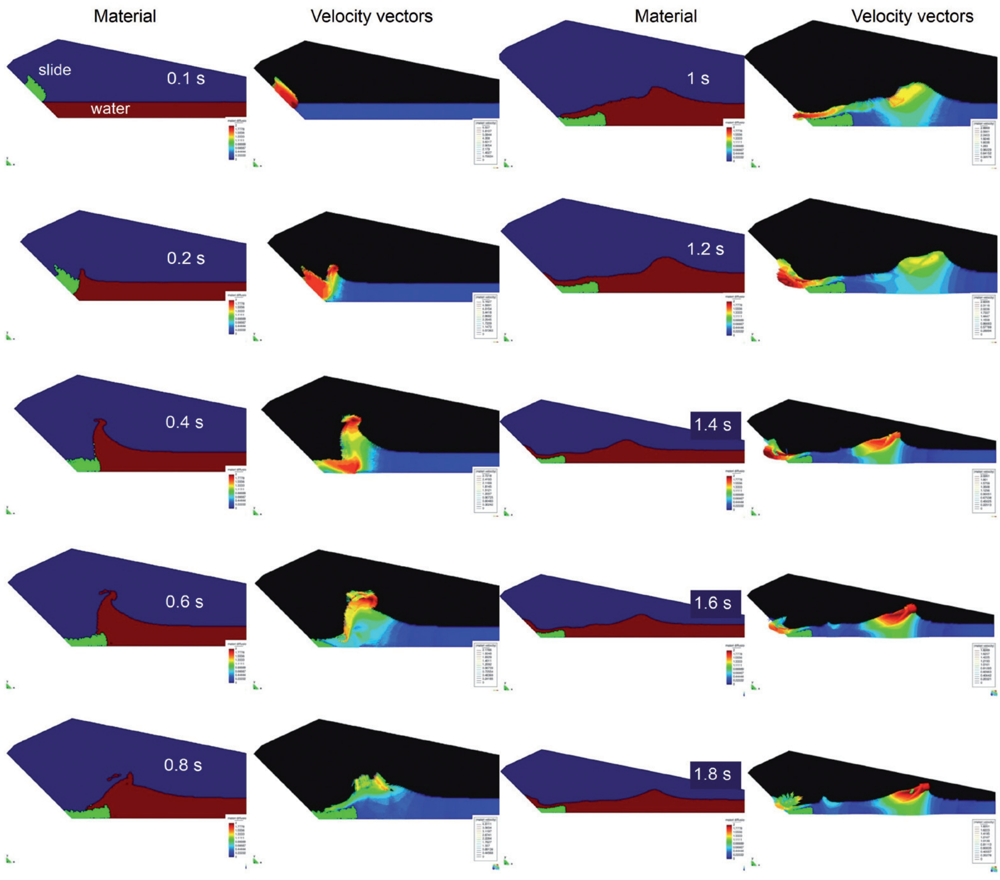

Fig. 9 - 2D simulation of a 0.118 thick granular avalanche with impact velocity = 5.4 m s-1 (Fr = 3.15). Material position and velocity vectors are represented at different time steps from the impact to the primary wave propagation

and lower properties for the old landslide material located on the opposite valley flank (ϕ = 13° to 7.5°, c = 100 kPa to 10 kPa reduced according to a plastic strain softening model).

The pre-failure and post failure topography have been obtained by available topographic maps (Rossi & Semenza, 1965), and recent Lidar surveys (Regione Friuli Venezia Giulia) which together with borehole data (Broili, 1967), geological cross sections (Rossi & Semenza, 1967) and field checks allowed to trace the failure surface geometry.

Figure 11 presents some of the results in terms of velocity vectors at two different instants. The average duration of the rockslide since its release to the arrest is about 51 s, a duration quite well comparable with previous estimations (Ciabatti, 1964) and records. The maximum water wave runup on the opposite valley side is very well simulated as well as the final deposit geometry and the water front splitting in an upstream and downstream direction. Back washing along the rockslide surface is well catched by the model (see bottom Figure 11; Viparelli & Merla, 1968).

The comparison between the streamlines geometry computed by the FE code for the rockslide and their real counterparts is also used for calibration. These are represented by the relative displacement vectors of well recognizable points and rocky outcrops mapped by Rossi &

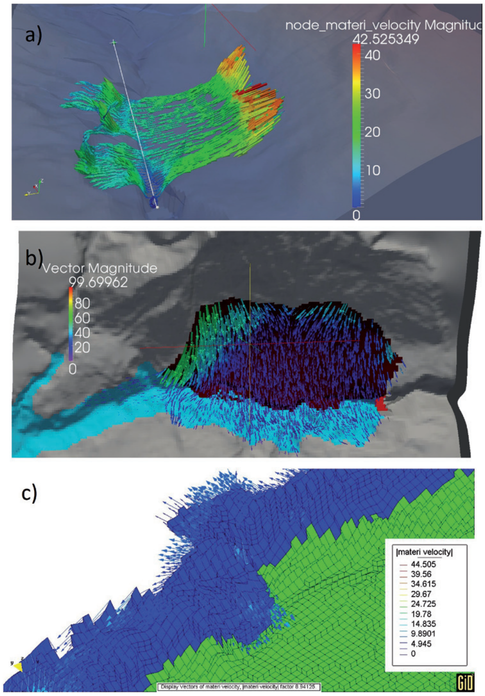

Fig. 11 - Fully 3D simulation of the Vajont rockslide and water wave top) and middle) velocity vectors after 21 s. In the middle the brown and cyan colors indicate the slide material and water wave respectively;bottom) water wave (in blue) propagation, partitioning and back wash over the rockslide body (in green) after 30 s

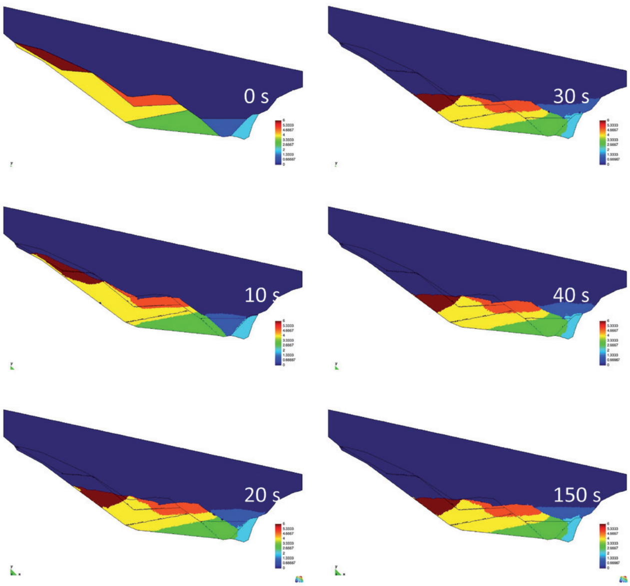

Fig. 10 - 2D model results of the Vajont rockslide with simulation of the water wave at different time steps till water becoming still. Landslide mass subdivided in different colors to evidence internal deformation. Light cyan colored mass on the right hand flank of the valley represents the paleo landslide material described by Rossi & Semenza (1965)

Semenza (1967) before and after the collapse and further support the prediction capability of the model and of the numerical approach.

Finally, the presented approach solve some of the assumptions commonly adopted in landslide-reservoir interactions, as the landslide rheology or mechanical behavior and its geometry during motion, and generation of the impulse wave (Ward & Day, 2011; Bosa & Petti, 2011).

CONCLUSIONS

The present contribution does not want to cover in depth the existing knowledge and literature concerning rockslides and rock-avalanche but suggests and discusses the relationships between monitoring and modelling as a continuous process leading to more satisfying predictions and hazard assessment.

Rockslides in alpine environments are complex phenomena which can require a careful monitoring, interpretation and analyses. Because of they characteristics a possible evolution in the form of a rock avalanche must be considered involving the possible erosion and impact against water reservoirs. As a consequence, the prediction capabilities of a FE code are presented against some experimental and real case studies. These case studies involve different slope geometry, thickness of erodible substrate, water depth to rockslide/avalanche thickness. Results of fully 2D and 3D simulations support the prediction capabilities and push further limits for numerical modeling of such phenomena.

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