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# LANDSLIDES SURFING ON WATER: A PRELIMINARY STUDY

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## ABSTRACT

We conjecture that in some cases, landslides impacting onto a water surface might acquire a vertical momentum that makes them slide horizontally at the water level, instead of plunging immediately into deep water, a process that we name surfing. An example of this behavior could be the recent (2002) landslide from the Sciara del Fuoco (Stromboli, Italy), which caused a tsunami with 10-15 meters high run-up waves. By examination of photographs, laboratory experiments, theoretical estimates, and numerical calculations, we preliminarily investigate the surfing conditions for landslides. The effect might also have an impact on the generation and propagation of tsunami waves.

## INTRODUCTION

It is well known that landslides impacting onto a water basin may generate potentially destructive tsunamis. In the last 230 years, two major tsunamis produced by the collapse of rapid massive landslides in water basins took place in Italy, causing more than 3500 casualties. Together with the Vajont disaster occurred on 6th October 1963 (Semenza, 2002), the 1783 Scilla event can be considered one of the most destructive tsunami induced by subaerial landslides (Mazzanti & Bozzano, 2011). Other similar events occurred in the last years in natural and artificial water reservoirs in Italy (Semenza, 2002) and in several other countries (see e.g., Mazzanti, 2008 for a review). Evidence of ancient catastrophic tsunamis induced by landslides in lakes were recently found also in Switzerland (Lucerna lake, Kramer *et alii,* 2012). These kinds of mixed landslides are also interesting in geomorphology for the reason that the impact with water tends to re-distribute the sediments through larger submerged areas.

The incidence of landslides that may potentially affect the hill slopes surrounding lakes is increasing due to the impoundment of several reservoirs for both water provision and hydropower energy. This is a common feature in Alpine environment (e.g. Italy, Switzerland, Austria), but also in several developed and developing countries like USA, China, Russia, India, or Ethiopia. Apart from huge disasters like the 1963 Vajont, several landslides do occur in artificial lakes during impounding phases or also under stationary conditions (e.g. Schuster, 1979). These problems have been recently outlined by the induced effects of a massive project like the Three Gorges Dam in China. As a consequence of rising water level in the huge basin, several landslides occurred along the bankside (Yusheng, 2010; Bolin *et alii*, 2010), often generating high waves. The one occurred in Gongjiafang slope on the 23 November 2008 induced a 30 m height wave thus causing severe economic impact (Bolin *et alii*, 2012).

Several authors have attempted to understand the main mechanism controlling the propagation of landslides entering a water basin and to derive information on the ensuing tsunami propagation. Laboratory experiments (Fritz *et alii*, 2003; Di Risio *et alii*, 2009; Mohammed & Fritz, 2010) and back analysis of past events (e.g., Freundt *et alii,* 2007; Mazzanti & Bozzano,

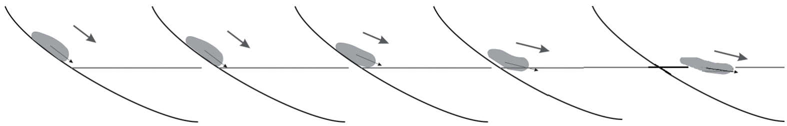


*Fig. 1 - Sketch showing the process of surfing as defined in the present work (time sequence from left to right). A landslide plunging at sufficiently low impact angle against a water reservoir, lake, or the sea, may be lifted a short time, so propagating nearly horizontally at the water-air interface*

2011) have been performed over the last years, leading to the development of ever-improving computer codes aimed at back simulating events already occurred and, potentially, to predict the tsunami impact related to future landslides. However, it is noteworthy that the basic mechanisms controlling the air to water transition of a landslide are still far to be exhaustively understood, and they have not perhaps attracted the required attention.

In a previous paper we preliminarily listed a series of simple observations apparently unnoticed or neglected in previous investigations concerning the impact of the mass with water and its propagation (Mazzanti & De Blasio, 2011).

In this paper we focus mainly on the surfing, i.e. a specific process that, to our knowledge, has not been formerly investigated with reference to landslides.. By analysis of video captured during real landslides, simple laboratory experiments and theoretical analysis (also supported by mathematical and numerical computations) we suggest that, under particular conditions, landslides might flow almost horizontally at the interface between water and air, before finally plunging into the water (Fig. 1). Such an effect might significantly modify the propagation of the landslide in the immediate phases that follow the impact with water, as well as the mechanics of tsunami generation.

Preliminary considerations about the conditions leading to the surfing process of landslides and the potential implications on the tsunami propagation and generation are herein presented. We will preliminarily consider the general physics of impact and surfing, while the process of tsunami generation by surfing landslides will not be addressed in detail.

## INVESTIGATING THE SURFING PROCESS ON LANDSLIDES

In order to assess whether and how surfing processes may affect the dynamics of coastal landslides impacting the water surface, in the present work we combine observation of real landslide events, simple laboratory experiments, and basic mathematical analysis.

### *FIELD OBSERVATIONS*

Some video recorded during the occurrence of oastal landslides apparently show the surfing effect. The most interesting has been shot by Dr. Massimo Pompilio of INGV (Istituto Nazionale di Geofisica e Vulcanologia), during the 29 December 2002 tsunamigenic landslide at Stromboli volcano, Italy (Chiocci *et alii*, 2008). Figure 2 shows some frames of the video. The granular avalanche travelled over the sea surface for more than 100 m in the span of few seconds, significantly increasing its front thickness before coming to rest. In this event, the surfing mass was only a part of the whole landslide volume. The remaining part of the mass probably travelled along the underwater slope like a debris avalanche, perhaps to be transformed into a turbidity current. Although the frames of Figure 2 show that the percentage of surfing mass was not negligible, it is difficult to give a precise estimate.

These effects have been recently observed in another interesting case on the three Gorges water basin on the Gongjiafang landslide in Wu Gorge occurred on November 23, 2008 (Bolin *et alii,* 2008). The sequence of frames reported on the paper by Bolin *et alii* (2008) shows that a percentage of the landsliding material remained at the water surface. Also in this case, the landslide velocity was moderate (up to 11 m/s). In spite of the density of the rocky material involved, it appears from the published figures that the landslide traveled a great deal horizontally before disappearing into the water, which is much deeper than the landslide thickness. Thus, a certain amount of surfing must have taken place.

Other indications could be based on the observation of old landslides deposits, rather than filmed events. For example, the chalk cliffs of Northern Europe exhibit long several tongues in correspondence of the scars produced by slope failures on the tidal flats (Hutchinson, 2002). Such mobility might have been promoted by surfing or perhaps also by hydroplaning on a light and impermeable medium (e.g., De Blasio, 2011). A rather extreme case of surfing could occur with ice avalanches collapsing in the fjords or


*Fig. 2 - Few frames from the video by M. Pompilio that show the 2002 landslide at Stromboli volcano. The whole sequence lasts about 4 seconds*

*Fig. 3 - Ice avalanches due to the failure of the front of glaciers on the oceanic water are likely to be a special case of strongly surfing landslides. Perito Moreno glacier, Argentina. Image Shutterstock, reproduced with permission*

the ocean (Fig. 3). Because ice is positively buoyant, surfing will become the leading effect in this case, even though such ice collapses are not particularly large or worrisome. One of the most important consequences of such events is the associated tsunami. It is well-known that the Stromboli avalanche produced a 15 m high tsunami that swept the coast of the island (Tinti *et alii*, 2005). Landslide-generated tsunamis have been studied in detail at least since the Grand Banks event of 1929 caused by a submarine landslide offshore Newfoundland (Fine *et alii,* 2005). However, landslides like the one of Grand Banks travel underwater from start to stop. When a landslide travels completely submerged the front causes water to rise above the unperturbed level, while the rear of the landslide draws it downward. In other words, water is perturbed vertically, while the shear impulse is negligible. In contrast, a tsunami generated by a landslide starting subaerially presents significant differences. The phase velocity of the tsunami wave becomes closer to the velocity of the landslide with a distinct amplification effect; moreover, a splash effect may create a high train of waves at once (Fritz *et alii,* 2003a; 2003b). We will suggest that surfing might affect the tsunami generation for a landslide starting subaerially

## *LABORATORY EXPERIMENTS*

Some research groups have performed experiments simulating landslides plunging onto a water reservoir (Fritz *et alii*, 2003, 2004; Freundt, 2003; Mohammed & Fritz, 2012). The laboratory experiments by Freundt (2003) aimed at simulating the occurrence of pyroclastic flows at the coastline, while the video by Freund *et alii* (2003) shows a bounce upon the water surface and a surfing effect at the early stages of the water impact.

In the mentioned papers, the landslide flow has been thoroughly investigated especially concerning the associated tsunami, while the possibility of surfing was not considered. On the other hand, preliminary experiments in a small flume partially immersed in a water tank showed a significant surfing effect of the granular material at the air-to water transition, similar to that observed in real landslides (Mazzanti & De Blasio, 2011). Specifically, different inclinations of the flume and three granular sizes were experimented. These simple tests showed a limited influence of the impact on coarse round grains, while evident surfing was observed with fine round grains (Mazzanti & De Blasio, 2011).

A sudden reduction in velocity upon impact resulted in the rising of the granular mass and a consequential thickening of the frontal part of the flow, with particles floating in the original mass. Over time, a significant increase of the area affected by floating was observed such that, following the impact, a portion of the mass was surfing at water level.

Surfing effects by using flat grains of argillite were even more evident. Single grains at the air-to water interface could topple and jump, sometimes nearly 2 m ahead of the impact point. Particles that did not jump were capable of floating and whirling into the water tank at high speed, sometimes travelling through meters-long distances. However, the irregular shape of the grains did not allow to perform controlled analysis and to attempt a scaling investigation.

Therefore, for the present work about 50 new tests were performed during the summer 2012 at the geotechnical laboratory of the University of Rome "Sapienza" (Department of Earth Sciences). The experimental setup consisted of a Plexiglas flume 1.5 m long and 15 cm wide, partially immersed in a pool filled by water and three disks of clay having density 1.3 kg/m$^3$, radius 10.5 cm and variables thicknesses (this leading to the following masses: 46.6 g, 90.5 g and 117.3 g). Figure 4 shows two typical experiments with the medium thickness disk of mass 90.5 g.

The experiment in A shows the behavior of the disk impacting the water pool at a speed of about 3 m/s. The plate is surfing to a long distance, yet always remaining submerged. In the experiment shown in B, the speed has been increased to about 5 m/s. In this case, the frontal drag force causes the plate to stand up after impact with water, and even to topple. This strong energy dissipation perturbs much the water surface, which makes the plate stop and promptly sink.

A qualitative analysis of the experiments allowed observing that surfing of disks is mainly controlled by the following features:

i) plates thickness (the thickest plate was seldom surfing);
ii) velocity;
iii) other tiny differences in the angle of impact, which are poorly controllable.

## THEORETICAL ESTIMATES

### *AIR TO WATER TRANSITION AND SURFING PROCESS: BASIC PRINCIPLES*

Several studies and experiments have been carried out since von Karman (1929) to find the impact forces of simple shaped objects such as spheres or disks against water. The sudden change of the ambient medium significantly affects both the further motion of the object and the water surface. Experiments show the complex mechanisms related to the transition mainly in terms of air cavitation, i.e., generation of air bubbles behind the object plunging in water during the initial stages of its submerged movement (Plesset & Prosperetti, 1977; Lee *et alii*, 1997) and shock on the impacting body (Fasanella *et alii*, 2003). A landslide is much larger than any experimental object, and also irregularly shaped. For this reason, the air-to water impact is more complex to understand and reproduce through laboratory experiments. Notwithstanding the importance of the air to water transition, little is known about the forces acting on an impacting landslide. The impact of intact rocky blocks against water have been considered from a dynamical viewpoint, albeit in a much approximated way (De Blasio & Mazzanti 2010; Mazzanti & De Blasio, 2011). In general terms, an object colliding against water with a velocity component normal to water $v_\perp$ is subject to a vertical impact force of the form

$$F_{IMPACT} \approx \frac{1}{2}\rho_W C_{IMP} v_\perp^2 S_{EFF} \quad (1)$$

where $S_{EFF}$ is the effective impact surface (i.e., the wetted area cut horizontally through the body), $v_\perp$ is the landslide speed perpendicular to water, $C_{IMP}$ is an impact drag coefficient, and $\rho_w$ is water density.

In practice, despite the relatively simple form of equation (1), its application to the case of a landslide impact may be more difficult than what one might expect. First of all, the impact drag coefficient is unknown for most situations and velocities. In a previous rockfall problem De Blasio & Mazzanti (2010) used the Shiffman-Spencer model for the drag (Shiffmann & Spencer,

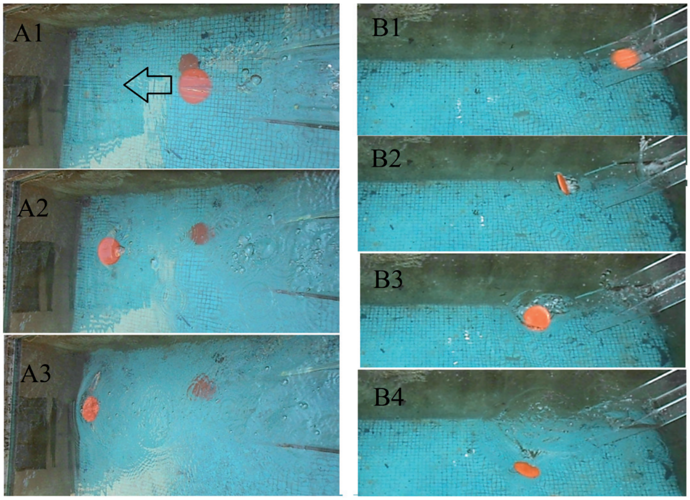



*Fig. 4 - Examples of two sequences A1-A3 and B1-B3 of simple experiments with a flat cylindrical plate built with modeling clay. The flume has an inclination of 35°. The only difference between sequence A and B is the disk velocity at the impact with water (3 m/s for A and 5 m/s for B). Note that in the "A" sequence the plate is surfing to a long distance, yet always remaining submerged. In "B", the frontal drag force makes the plate to topple*

1945; Moghisi & Squire, 1981). However, the precise values at high speed even for a simple sphere or cylinder are poorly known.

Moreover, the permeability of the landslide material is strongly affected by the presence of fines clogging the pores of the fragmented landslide material, and it is difficult to understand whether the basal layers of a fragmenting landslide are impermeable to water. In addition, the landslide material is deformable and assumes complicated shapes during and after the impact.

For simplicity, in a first estimate we shall be considering the landslide material as rigid, at least during the first stage of the impact. From Eq. (1), the effective vertical acceleration $g_{EFF}$ upon impact with the water has the functional form of the kind

$$g_{EFF} \approx -g\left(1-\frac{\rho_W}{\rho}\frac{\Delta V}{V}\right)+\frac{1}{2}\frac{\rho_W}{\rho}C_{IMP}v_\perp^2\frac{S_{EFF}}{V} \qquad (2)$$

where $V$ is the volume of the model landslide, $\rho_w$, $\rho$ are the densities of water and of the landslide respectively, $\Delta V$ is the submerged volume, $C_D$ is an impact drag coefficient. Eq. 2 shows that the gravity acceleration may be strongly reduced by the impact (second term on the right hand side) in addition to buoyancy of the submerged part.

The strong reduction of the vertical acceleration does not have an equivalent counterpart concerning the horizontal acceleration, which will be of the kind

$$a_{EFF} \approx -\frac{1}{2}\frac{\rho_W}{\rho}C_{SK}u^2\frac{S_{EFF}}{V} \qquad (3)$$

where $u$ is the horizontal velocity (parallel to the water level). Owing to the smaller value of the skin friction drag coefficient $C_{sk}$ compared to the impact drag coefficient (typically $C_{SK} \approx 10^{-3}$-$10^{-2}$; $C_{IMP} \approx 1$), the contribution in Eq. (3) is much smaller than the one in Eq. (2).

A different but related phenomenon can potentially shed light on this hypothesis. The most spectacular and dangerous mass flows which exploit a kind of surfing process are pyroclastic flows. As already mentioned, some papers have considered the surfing of pyroclastic flows reaching the sea through theoretical analyses, laboratory experiments (Freundt, 2003; Legros & Druitt, 1999) and back analysis of real cases like the 1883 Krakatau eruption (Carey *et alii,* 1996). Once a pyroclastic flow reaches the sea, several mechanisms take place like phreatic explosions mainly related to thermodynamic phase transition from water to vapor, which may change the flow behavior and make it flow horizontally. Catastrophic consequences are exemplified by the cases of Krakatau 1883 and Vesuvius 79 A.C (Carey *et alii,* 1996). The burning dust from Krakatau, moving over the sea, reached some islands several km away from the volcano maintaining high velocity and lethal temperatures. These phenomena represent a dramatic example of the importance of water surface in controlling the evolution of natural gravity flows coming from a subaerial environment.

## *SURFING OF A RIGID BODY: A SIMPLE MODEL*

In order to simulate the impact of a landslide onto a water reservoir (5A) we make some theoretical estimates of a simple object (such as the one shown in 5B) falling against water perpendicular to its base with a velocity v. The object consists of a cylinder of radius $R_i$ and height $T_2$ with a basal spherical sector of height $T_1$ and radius of curvature R.

This geometry is similar to disks used in the experiments of Figure 4 and can be useful to analyse the impact of more complex landslide geometries. Furthermore, it is noteworthy that the explicit introduction of the radius of curvature at impact may allow to explain the importance of the angle of impact of a landslide in the reservoir for surfing to occur.

The total volume of this object is:

$$V = \pi \left[ \frac{1}{3} T_1^2 \left( R - T_1 \right) + T_2 R_{\text{int}}^2 \right] \qquad (4)$$

The equation of motion of the object (neglecting the added mass effect) is

$$\frac{dU}{dt} \approx -g \left( 1 - \frac{\rho_W}{\rho} \frac{\Delta V}{V} \right) + \frac{1}{2} \frac{\rho_W}{\rho} C_D v_\perp^2 \frac{S}{V}. \qquad (5)$$

The factor $\Delta V / V$ is the ratio between the submerged volume and the total volume of the object as a function of the depth reached by the landslide.

Having approximated in this simple model the shape of the landslide at the contact with water as the portion of a sphere, the cross-section surface is approximated as the one of a spherical sector and so

$$S = \pi \left( 2R\,\Gamma - \Gamma^2 \right) \qquad (6)$$

where $\Gamma$ is the depth reached by the sphere, and

$$\Delta V = \frac{1}{3} \pi\, \Gamma^2 \left( R - \Gamma \right). \qquad (7)$$

We now assume that the impact with water occurs with the object moving at an angle $\beta$ with respect to the horizontal, and not vertically. The ratio between the impact and the gravity force (accounting also for buoyancy) is so

$$\eta \approx \frac{1}{2} \frac{\rho_W}{\rho} \frac{C_D v_\perp^2 S \sin^2 \beta}{gV \left( 1 - \frac{\rho_W}{\rho} \frac{\Delta V}{V} \right)} \qquad (8)$$

Figure 6 shows the ratio between the impact and the gravity forces as a function of the depth of the modelled landslide speed for different radii of curvature, assuming that the base of the object is submerged by 5 m of water. Note that the ratio approaches unity for large radii of curvature and high speeds (the impact force increases with the square of the speed, as evident from the equation 8). The relevant role of the radius of curvature is also easily explained: when the radius of curvature is small, the area of the submerged landslide remains small as the object dips into the water reservoir, while for a large radius it strongly increases, allowing for an effective increase of the impact force. This is probably a key effect in surfing.

Coming back to the landslide, 5A and 5B show that the same landslide falling into the water reservoir may impact with two different effective radiuses of curvature depending on the angle of impact: 5C shows an impact with relatively small angle, corresponding to large radius of curvature, while 5D an impact with small radius of curvature. From the previous analysis, the second landslide benefits more of the surfing effect from the impact energy (Fig. 6).

The difference between the two situations may be large for a landslide that is very flat but with a sharp tip. This also indicates that the angle of impact affects dramatically the surfing effect.

It is worth to note that a landslide may benefit from the surfing effect even if the ratio $\eta$ is less than one. This is because a landslide that has much reduced vertical acceleration may avoid contact with the bottom of the sea or lake and thus hydroplane; the missing contact with the basin will promote mobility in this case.

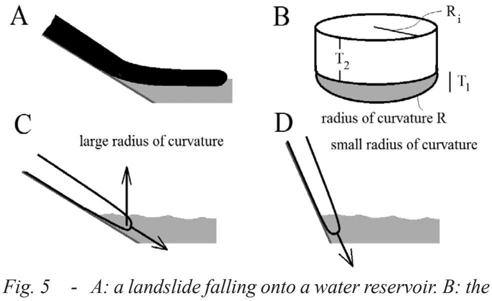



*Fig. 5 - A: a landslide falling onto a water reservoir. B: the approximated shape used for a simple theoretical analysis. C: The impact at low angle corresponds to an impact of an object like in B with large radius of curvature. In a more head-on impact (D), the landslide impinges with small radius of curvature*

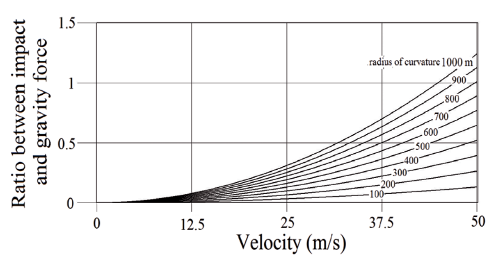



*Fig. 6 - The ratio η between the impact to gravity forces as a function of the speed for an object shaped like that in 5B plunging at an angle β=45$^0$, $C_D$=1.5 p=2200kg/m$^3$ $T_1$=10 m; $T_2$=8 m. The data refers to the point at which the object is immersed in 5 m of water. The density less than that of basaltic rock is justified considering that the rocks of Stromboli are often pumiceous*

Theoretically, a necessary condition for surfing is that upon impact the total vertical acceleration becomes directed against the gravity field, which leads to

$$v > \sqrt{2g\frac{\rho}{\rho_W}\frac{V/S}{C_D \sin^2\beta}\left(1-\frac{\rho_W}{\rho}\frac{\Delta V}{V}\right)} \equiv v_{CRIT} \quad (9)$$

where $v_{CRIT}$ is the critical velocity for surfing. Hence, for plausible parameters of a 10 m deep landslide, critical velocities would be of the order 20 m/s.

However, a landslide such as Gongjiafang was surfing at speeds 50% lower that the critical value calculated with Eq. (9). Apart from uncertainties that may justify a deviation of this order probably we must consider that surfing occurrence is probably easier that the eq. 9 would suggest.

Note that a vertical acceleration upon impact does not necessarily imply a bouncing of the landslide, because even if the acceleration changes sign, the velocity may not do so.

## *SURFING OF A DEFORMABLE BODY: A NUMERICAL SIMULATION*

In order to improve the simple above analysis, we have also developed a numerical model for a landslide impacting against a water reservoir using a molecular dynamics approach (Campbell, 1990). This method consists of substituting the debris mass with a set of particles, each representing a block, modelled as two-dimensional disks. The model thus allows in a natural way for the deformation of the landslide mass. In a previous version for subaerial landslides, the force $T_I(X_I-X_J)$ acting on the block due to contact with block is written as

$$\vec{T}_i(\vec{x}_i-\vec{x}_j) = \vec{R}_i(\vec{x}_i-\vec{x}_j)+\vec{A}_i(\vec{x}_i-\vec{x}_j)+\vec{C}_i(\vec{x}_i-\vec{x}_j)+\vec{D}_i(\vec{x}_i-\vec{x}_j) \quad (10)$$

where $X_I$ and $X_J$ are the positions of the two blocks. The total force acting on *i* results from four elementary units: i) $R_I(X_I-X_J)$ a repulsive force simulating the hard-core repulsion when blocks interpenetrate, ii) $A_I(X_I-X_J)$ an attractive force simulating cohesion, iii) a shear Coulomb force $C_I(X_I-X_J)$ resulting from friction, and finally iv) a dissipative force $D_I(X_I-X_J)$.

The acceleration of the block is so

$$\frac{d^2\vec{x}_i}{dt^2} = \vec{g}\left(1-\frac{\Delta V\rho_W}{M}\right)+\frac{1}{M}\sum_{j\neq i}\vec{T}_i(\vec{x}_i-\vec{x}_j)+\frac{\vec{F}_G}{M}-\frac{\rho_W C_D\vec{v}|\vec{v}|\pi R^2}{2M} \quad (11)$$

where M is the block mass, Δv its submerged volume, $F_G$ is the impact force with the terrain, R is the block radius, g is gravity acceleration, and the last term is introduced here to deal with water impact and flow, where $C_D$ is the drag coefficient. In accordance with Shiffman & Spencer (1945) and Moghisi & Squire (1981), $C_D$- varies between the situation at impact with the water surface when it attains its highest value, and the situation of total immersion. Models of rock avalanches based on molecular dynamics have been widely used for the description of dry granular flows (Campbell, 1990; Campbell *et alii,* 1995). In previous work, an attractive force was introduced to simulate a cohesive debris flow (De Blasio, 2009). The model presented here also features the impact and drag with water (first and last terms on the right hand side of Eq. 11).
By testing different plausible values of density, impact geometry and impact coefficients, we found that the results vary greatly between situations in which surfing is favoured ("strong" surfing) to those of weak surfing.

In Figure 7 the case of a configuration experiences surfing is presented. More specifically, Figure 7A shows the simulated sequence of a landslide collapsing into a water reservoir at different times (the water is at "0" height). The granular mass is led to collapse against a gate that is than "removed" numerically after 20 s. After removal, the landslide slips along a relatively steep chute. When reaching the water surface, blocks tend to travel more horizontally, thus remaining at the front of the landslide. Then, new falling blocks form a partly submerged plug with tendency to grow on the subaerial side, and which is thrust horizontally by the falling blocks. Figure 7B at the bottom shows the velocity as a function of time.

Figure 8 shows the corresponding results for a weak surfing case (obtained lowering the impact coefficient and increasing effective gravity, i.e., gravity acceleration acting upon a completely submerged body). Note that in this case the landslide tends to plunge more promptly into the water without forming a subaerial plug.

## DISCUSSION AND CONCLUSIONS

We have suggested that once a landslide mass impacts on the water surface, the transition between the subaerial and the subaqueous environment could cause a drastic reduction of the vertical acceleration. As a consequence, the momentum of the landslide is largely modified after the impact and transition phase and the velocity become much more parallel to water than it was before impact. This process, here called "surfing", is suggested by photographic sequences of past coastal landslides, laboratory experiments, mathematical analysis and numerical simulations. However, not all the



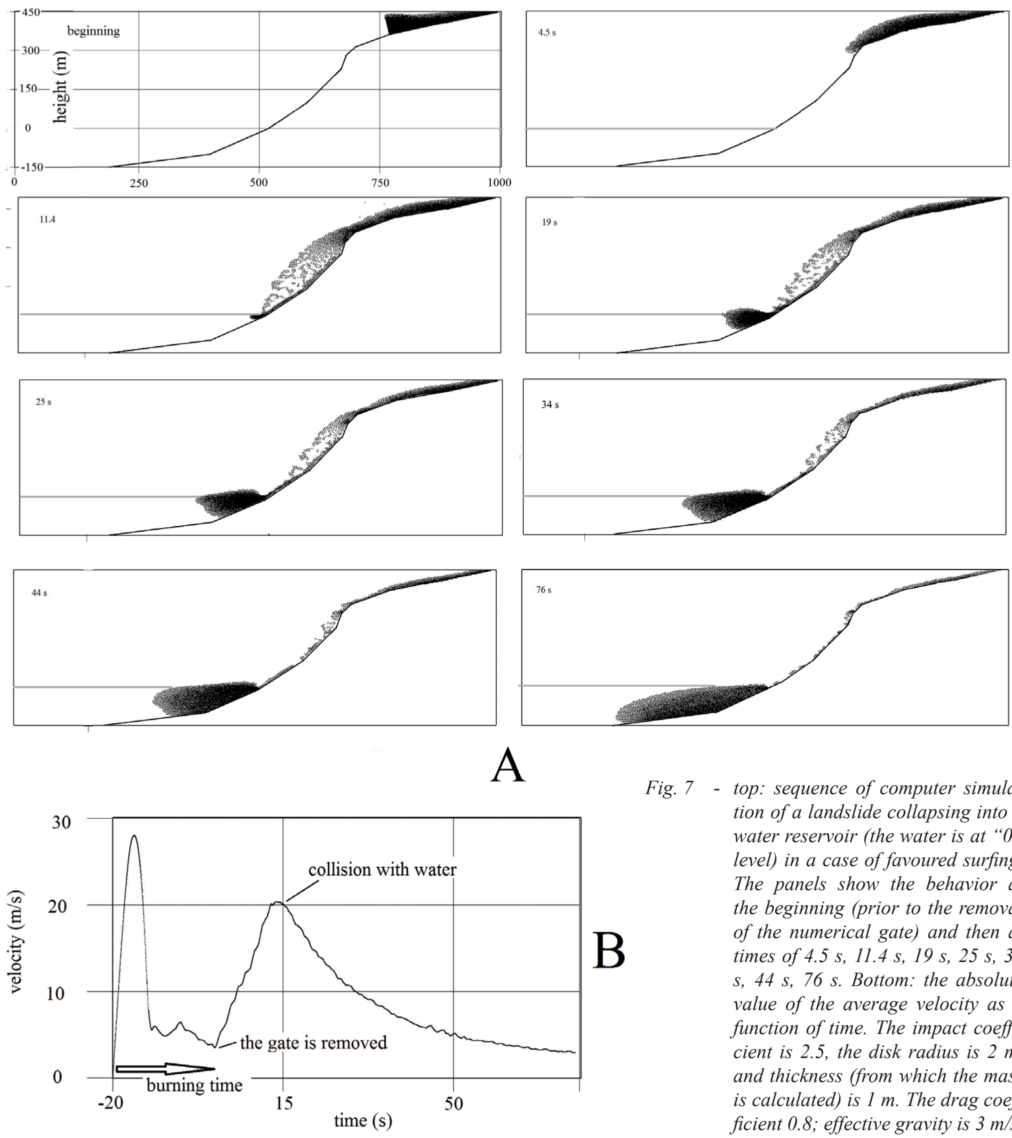



*Fig. 7 - top: sequence of computer simulation of a landslide collapsing into a water reservoir (the water is at "0" level) in a case of favoured surfing. The panels show the behavior at the beginning (prior to the removal of the numerical gate) and then at times of 4.5 s, 11.4 s, 19 s, 25 s, 34 s, 44 s, 76 s. Bottom: the absolute value of the average velocity as a function of time. The impact coefficient is 2.5, the disk radius is 2 m, and thickness (from which the mass is calculated) is 1 m. The drag coefficient 0.8; effective gravity is 3 m/s$^2$*

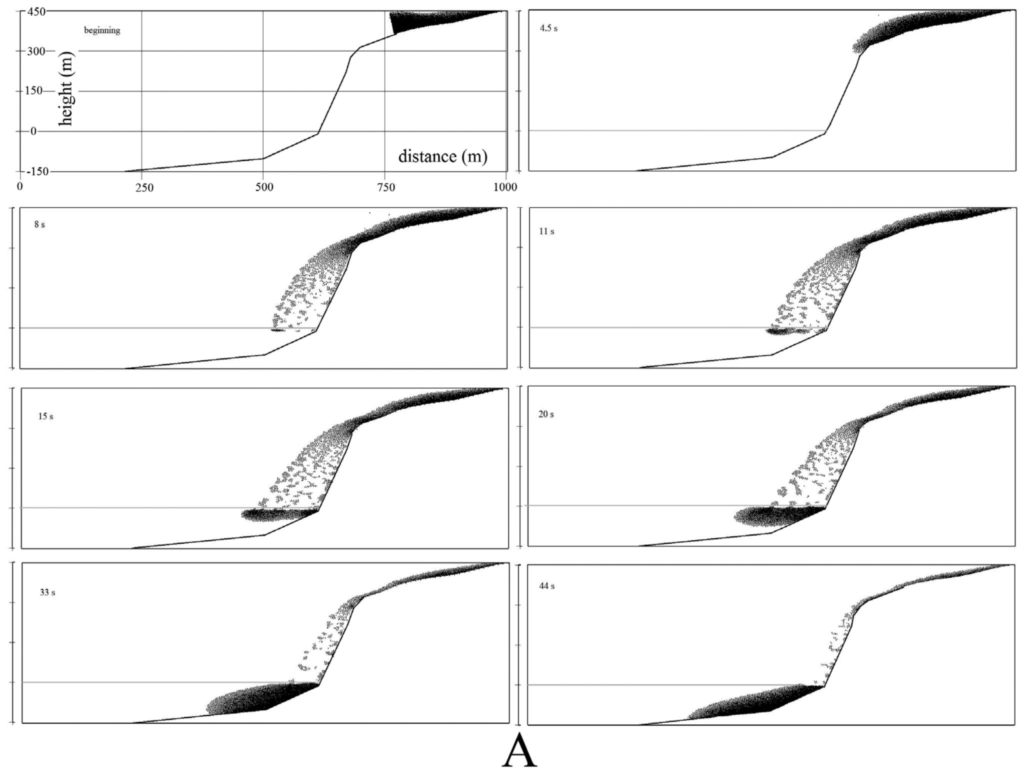
landslides may potentially give origin to this kind of process. For example, it is unlikely that the very thick Vajont landslide has surfed during the event of 1963.

Different factors like the speed, impact angle, thickness, density and permeability of the mass are likely to strongly affect the impact with water of a landslide starting subaerially and plunging into a water basin. However, the controlling factors are at present difficult to be constrained quantitatively.

We suggest that surfing will likely occur if several favorable conditions are satisfied, some of which have been addressed in the present work. The following are probably the most relevant features that can facilitate the occurrence of the process:

i) low density of the moving mass;
ii) rounded snout of the mass;
iii) impermeable material due to fines clogging the pores;
iv) high speed at the impact against water with gentle slope angle.

We speculate that surfing of a landslide on the water surface can significantly affect also the underwater propagation of the landslide and, consequently the induced tsunami generation.



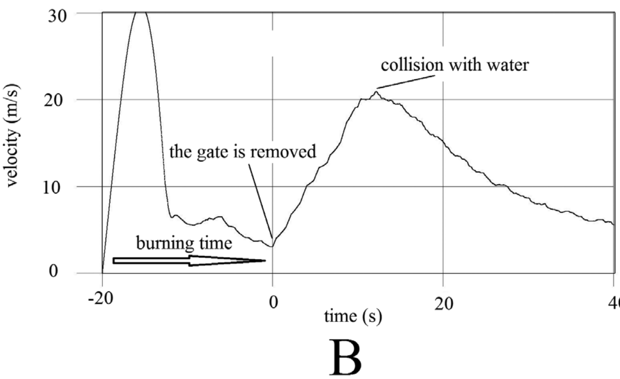




*Fig. 8 - A: sequence of computer simulation in a case of weak surfing. The panels show the behavior at times of 4.5 s, 8 s, 11 s, 15 s, 20 s, 33 s, 44 s. B: the absolute value of the average velocity as a function of time. The impact coefficient is 2.0, the drag coefficient 0.8; effective gravity is 5 m/s²*

To clarify how the water-impact can affect the tsunami potential, two different phases could be considered separately: 1) the impact and, 2) the subsequent flow behavior.

Regarding the impact phase, FRITZ *et alii* (2003) showed that a thick landslide impacting against water at high velocity creates a hydrodynamic crater which significantly increases the volume of displaced water and hence the wave height. In their experiments, these authors use constant slope angle of 45° and one single type of granular material. However, the hydrodynamic impact crater is strongly influenced by the inclination, velocity and type of material. Large bubbles created at the impact by cavitation may develop with coarse round grains, but are probably absent with smaller grains.

The surfing effect was not discussed by FRITZ *et alii* (2003) even though it seems to occur in their experiments especially with fine and flat coarse grains. A large volume of the hydrodynamic impact crater can be observed exactly when the surfing effect does not occur (MAZZANTI & DE BLASIO, 2010). Hence, it can be conjectured that the experiments showing hydrodynamic cratering as the leading effect (FRITZ *et alii,*

2003) are a consequence of the coarse round grains used for the experiments, and cannot be generalized to different types of landslides.

In this work, however, we concentrated more on the subsequent flow behavior (point 2). After a landslide has impacted against the water it may either promptly descend into the reservoir, or surf (completely or, more probably, partially upon the water surface) before plunging into the water. We suggest that tsunamis generated by surfing landslides may be different from those due to landslides descending at once, as the former tend to "shovel" water in the front, rather than perturbing it from below. Thus, waves generated by a surfing landslide will resemble more those by a fast-moving ship, with a characteristically different dynamics. It would be interesting to understand whether the surfing effect, which can significantly reduce the hydrodynamic impact crater, will consequently lessen the tsunami potential as well, or perhaps increases it, owing to the water horizontal movement.

The front thickening due to the impact might also accentuate the tsunami potential (Harbitz *et alii,* 2006; Fritz *et alii,* 2003; 2004). In addition, the back-tilting effect of the mass might also play a non-negligible role facilitating the injection of a water wedge beneath the landslide body, and thus triggering the hydroplaning effect (so delaying the contact of the landslide with the bottom). The occurrence of hydroplaning, with its characteristically reduced friction at the base, significantly increases the landslide velocity and travel distance and thus its tsunamigenic potential. It is clear that, as also shown by our simulations (compare Figs. 7 and 8), a landslide will in any case increase its run-out by surfing.

Perhaps surfing is a more common occurrence than previously thought. It is possible that the scarcity of filmed sequences of failure along the coasts have prevented researchers from recognizing the occurrence and perhaps even commonness of the effect. However, the commercial success of mobile smartphones and non-professional video cameras implies an increasing chance of collecting videos of sudden and unpredictable catastrophic events, which will likely improve the data available.

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