Simulation of Submarine Landslides by Cellular Automata Methodology

V. Avolio Maria, Bozzano Francesca, Di Gregorio Salvatore, Lupiano Valeria, and Mazzanti Paolo

Abstract

Numerical modelling is a powerful tool for assessing risk related to submarine landslides and their possible consequences (i.e. impact on structures, induced tsunamis, etc.). To this aim, the simulation of the propagation phase of flow-like landslides is particularly important. A new model (named SCIDDICA-SS2), which is based on the Macroscopic Cellular Automata computational paradigm, has been specifically designed for the simulation of coastal and underwater landslides. SCIDDICA-SS2 is a fully 3D model based on the equivalent fluid approach. It accounts for the most important mechanism controlling the propagation of an underwater landslide as well as peculiar mechanisms like erosion of the seabed, hydroplaning and air to water impact (in the case of coastal landslides). The 1997 debris flow (subaerial–submerged landslide) at Lake Albano (Italy), the 2008 submarine debris flow at Bagnara Calabra (Italy) and the 1888 submarine debris flow at Trondheim (Norway) have been simulated by SCIDDICA-SS2, showing its high performances in simulating submarine landslides.

Keywords

Cellular automata • Flow-like landslides • Modelling • Propagation • SCIDDICA

Introduction

Landslides are common events on the earth's surface and their impact on the community is quite evident. However, several landslides occur even underwater and sometimes can be particularly dangerous (Hampton et al. 1996). Underwater landslides may cause serious damage to gas and oil platforms as well as to transmission lines. Furthermore, they can generate tsunamis with a strong impact on coastal communities (Hampton and Locat 1996).

Catastrophic events occurred in the last decades highlight the risk related to tsunamis in coastal areas especially if the increasing population living in coastal regions is considered.

However, the investigation and analysis of submarine regions is very difficult, therefore numerical modeling may be considered an important support for studying underwater landslides and assessing the induced risk (De Blasio 2011).

Underwater landslides are ruled by similar mechanics to that of their subaerial counterparts. However, in coping with the modelling of submarine mass movements, several important differences due to the different medium (water instead of air) must be accounted for (Mazzanti 2008).

In this paper we focus on flow-like landslides (Hungr et al. 2001), i.e. landslides characterized by a fluid-dynamical behaviour after failure. These landslides, such as debris-flows and debris-avalanches are among the most

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dangerous events both in the subaerial and in the submarine environment.

These landslides may attain enormous distances, especially underwater, and can reach very high speed (De Blasio 2011). Furthermore, they are the events that most frequently trigger tsunamis.

However, the mechanics ruling subaerial and even more subaqueous flow like landslides are complex, involving properties similar to those employed in fluid, particle, and soil mechanics. Frictional interaction between grains, viscous and cohesional behavior of clays, and collisional dampening by pore-water all rule the transfer of momentum within such a type of landslides. Furthermore, additional particular mechanisms like hydroplaning seem to play a relevant role in the dynamics of submarine flow-like landslides (Mohrig et al. 1998; De Blasio et al. 2004).

Modelling such a system particle-by-particle inevitably is computationally cumbersome. Hence, the most used models are based on the equivalent fluid approach, which assumes simplified rheological models to approximate the flow behaviour of a flow like landslide. For example, on the basis of Herschel–Bulkley, Bingham and bilinear rheologies, Jeffrey G. Marr and co-authors (Maar et al. 2002) developed the numerical code BING for the simulation of submarine debris/mud flows. This numerical model is based on explicit finite differences. BING can be considered as the first numerical model specifically developed for submarine landslides. However, it is affected by several limitations since it does not account for the 3D geometry of the seabed, erosion, entrainment of water and so on.

On the other side, complex models based on a 3D framework have been developed, especially for subaerial landslides using the equivalent fluid approach and different rheological models (Hungr 1995; McDougall and Hungr 2004 Denlinger and Iverson 2001; Pirulli and Marco 2010, amongst others).

Some methods have been also recently developed to extend the application of these models to submarine and coastal landslides (Mazzanti and Bozzano 2009).

A different approach to simulate submarine flow-like landslides (Avolio et al. 2008, 2009, 2010; Mazzanti et al. 2009) has been recently proposed, based on the framework of Macroscopic Cellular Automata (MCA).

In this paper the SCIDDICA-SS2 model will be presented together with its application to some real cases of submarine landslides.

Cellular Automata (CA) Approach

CA were introduced for the first time by John von Neumann (von Neumann 1966). The methodology adopted in CA models is generally empirical-inductive, i.e. trying to identify the basic mechanisms that control the overall behaviour of an observed phenomenon and attempting to find simple laws that determine the interaction mechanisms among the basic components. Subsequently, one defines a model that translates in formal terms the identified laws and adopts a verification phase prior to a monitoring one, necessary to evaluate the reliability of the model in relation to the real phenomenon.

A CA is a mathematical representation of a physical system, whose space (1/2/3 dimensions) is divided into simple, regular, uniform size parts called cells. Each cell embeds an elementary, identical, computation unit *fe* (a finite automata), whose states identify the properties of the portion of space corresponding to the cell which are considered “significant” for the evolution of the phenomenon. The *fe* input of a cell c is given by the states of m neighbouring cells, including the cell c. The neighbourhood conditions are determined by a pattern which is invariant in time and constant over the cells.

At step 0, all *fe* are in arbitrary states, describing the initial conditions of the system; then, the CA evolves changing the state of all cells simultaneously at discrete times (CA step), according to the rules operated by what is called the *transition function*: $\tau{:}S^m \rightarrow S$. Complex macroscopic phenomena, like debris flow (DF), need an extension of the original CA definition (MCA) (Di Gregorio and Serra 1999) in order to fit the modelling requirements of many macroscopic phenomena. In MCA, major novelties regard the *state* of a cell, which is decomposed in “*sub-states*”, each one representing a particular feature (e.g. lava temperature, debris amount, etc) of the phenomenon to be modelled, and precisely, the state values of a cell is defined at the centroid of the cell, are assumed as representative of the entire cell. In addition, in MCA some “parameters” are generally considered, which allow to “tune” the model for reproducing different dynamic behaviours of the phenomenon of interest (e.g., thresholds concerning minimum possible outflows from a cell toward a neighbour one). Moreover, even the state transition function is split in “elementary processes”, each one describing a particular aspect of the considered phenomenon (e.g., detrital cover mobilization).

The model here adopted (and described herein) to simulate complex macroscopic phenomena, as in other models for simulating lava flows, landslides, etc. (Avolio et al. 2003), is two-dimensional in order to keep the model as simple as possible. Furthermore, cell features concerning the third dimension (i.e., the height), e.g., “cell average altitude”, “debris thickness in the cell”, “debris kinetic head” etc, are defined as sub-states (Di Gregorio and Serra 1999), specified better in the following, and thus the third dimension varying features are enclosed in the states of the cells or may be introduced (e.g. vertical variation in debris density may be approximated in the cell by sub-states “layers”, that may be expressed as a variable thickness, related to a fixed range of density values). For these reasons, the model can be considered fully 3D.

In fact, another peculiarity of this type of MCA model is that it is possible to consider characteristics of the *cell* (i.e. *sub-states*), typically expressed in terms of volume (e.g. debris volume), in terms of thickness. This simple assumption permits to adopt an efficacious strategy that computes *incoming* and *outgoing* flows of a physical quantity (that is, in case of SCIDDICA-SS2, landslide material) from the central cell to the neighbouring ones, by leading to variations of its height, in order to minimize the non-equilibrium conditions. This equilibrium state is attained by considering interactions between each cell and its surrounding neighbours. By applying this idea to every neighborhood in the lattice, the whole system is driven to the most stable configuration by the *Minimization of Differences* algorithm (Di Gregorio and Serra 1999).

MCA were proposed for the first time in 1982 to model the dynamics of macroscopic spatially extended systems, and firstly applied to the simulation of basaltic lava flows (Crisci et al. 1982). Since then, MCA were adopted for the simulation of diverse natural phenomena: pyroclastic flows (Avolio et al. 2006), snow avalanches (Barpi et al. 2007; Avolio et al. 2010b), density currents (Salles et al. 2007) and, in particular, both subaerial–submarine flow type landslides by our research group (for an extended bibliography see Avolio et al. 2010a) and others (Segre and Deangeli 1995, Clerici and Perego 2000).

Among existing Macroscopic Cellular Automata models, we will focus on SCIDDICA, a family of deterministic MCA models, specifically developed for simulating DF. This model has been developed according to an incremental strategy, permitted by the underlying CA properties, that allow to build a model by the composition of "*elementary processes*". This permits to consider first models of the family for less complex case studies. Subsequently, new versions are generated step by step by introducing other "*elementary processes*" in order to model more complex real cases.

A general description of the model SCIDDICA-SS2 will be given in next sections, together with the results of some applications to real cases of only submarine and both subaerial – submarine landslides.

SCIDDICA-SS2 Model: General Framework

SCIDDICA is a family of deterministic MCA models, specifically developed for simulating flow like landslides. The latest version, SCIDDICA-SS2, introduces new features, with respect to previous versions of SCIDDICA (Avolio et al. 2008), (Avolio et al. 2010). This release is an extension to combined subaerial-subaqueous flow-type landslides, with a new flows characterization according to the position and velocity of the centre of mass (Avolio et al. 2008, 2009). Hence, SCIDDICA-SS2 can be considered as the only "global model" for landslides, able to simulate both subaerial, submarine and mixed landslides. Furthermore, a new release of SCIDDICA for extra-terrestrial landslides has been recently designed.

Constitutive features of the equivalent fluid, which are expressed by some SCIDDICA-SS2 parameters, cannot be sometime measured in laboratory when they represent fictitious statistical properties, and are determined by back analyses of real cases.

SCIDDICA-SS2 is a two-dimensional MCA with hexagonal *cells*. Formally, SCIDDICA-SS2 can be defined as follows:

$$\mathrm{SCIDDICA} - \mathrm{SS}_2 = <R, X, S, P, \tau>$$

where:

- R identifies the cells, covering the finite region, where the phenomenon evolves;
- X is the cell neighbourhood relation, that includes the cell itself and its adjacent cells;
- S is the finite set of states of the *fe*, embedded in the cell; it is equal to the Cartesian product of the sets of the following *sub-states*: S_a(cell altitude, in meters); S_{th} (thickness of landslide debris, in meters); S_x and S_y (coordinates of the debris barycentre with reference to the cell centre, in meters); S_d (maximum depth of detrital cover that can be transformed by erosion in landslide debris, in meters); S_E (total energy of landslide debris, in joule), S_{kh} (debris kinetic head, in meters); ${S_{oi}}^6$ and ${S_{oe}}^6$ (debris outflows toward the six adjacent cells: internal part that remains inside the central cell, external part that penetrates the adjacent cell, normalised to a thickness, in meters); ${S_{ex}}^6$, ${S_{ey}}^6$, ${S_{ix}}^6$ and ${S_{iy}}^6$ (barycentre coordinates of the debris external and internal outflows with reference to the cell centre, in meters);
- P is the finite set of parameters which account for the general frame of the model and the physical characteristics of the phenomenon (e.g the size s of the cell specified by the cell side or the apothem and the time correspondence to a MCA step t);
- τ is the MCA deterministic transition function that is applied, step by step, to all the cells in R, the MCA configuration changes obtaining the evolution of the simulation.

Initial conditions are specified by primary values of *sub-states*: S_{th} is zero everywhere except for the detachment area, where the thickness of landslide mass is specified. S_a and S_d

are the morphological height and the initial depth of detrital cover, respectively. S_E at step 0 represents only the potential energy, related to debris mass. All the values related to the remaining *sub-states* are zero.

In the following, a sketch of the main local elementary processes of the transition function of SCIDDICA-SS2 will be given.

Altitude, kinetic head and debris thickness vary by detrital cover mobilization. When the kinetic head value overcomes an opportune threshold p_m, a mobilisation of the debris cover occurs, which is proportional to the quantity overcoming p_m; variation, Δ, of involved *sub-states* is computed as:

$$\Delta S_D = \Delta S_A = \Delta S_{TH} = p_e(S_{KH} - p_m)$$

where p_e is an empirical parameter, which quantifies the progressive erosion.

Debris outflows (thickness, barycentre co-ordinates, kinetic head) are blocks whose bulk is determined by the minimization algorithm, that accounts also for energy. Their barycentre shift (*sh*) towards a neighbourhood cell is computed according to the following motion equation in the subaqueous context:

$$sh = \left(\frac{1 - e^{-\alpha t}}{\alpha}\right)\left(v_0 - \frac{g'(\sin\theta - \mu\cos\theta)}{\alpha}\right) + \left(\frac{g'(\sin\theta - \mu\cos\theta)}{\alpha}\right)t$$

This shift formula for subaqueous debris considers the slope θ between the central cell and its adjacent, the initial velocity $v_0 = \sqrt{2g'S_{KH}}$, the coefficient of friction μ and considers also the water resistance, using modified Stokes equations with a form factor, α, proportional to mass and $g' < g$ (g the acceleration of gravity), where g' accounts for buoyancy and is dependent on the density of the material of the landslide (Avolio et al. 2008).

Composition of debris inside the cell (remaining debris more inflows) and determination of new thickness, barycentre co-ordinates and total energy is calculated considering internal and external flows and computing all *sub-states* in terms of weighted average formulae, and new thickness of debris and its kinetic and potential energy are so updated.

The effect of turbulence is modeled by a proportional kinetic head loss:

$$-\Delta S_{KH} = p_{td} S_{KH}$$

where p_{td} is energy dissipation parameter by turbulence.

SCIDDICA-SS2: Submarine Landslides Case Histories

The SCIDDICA-SS2 model has been applied over the last years to the simulation of several subaerial, submarine and coastal landslides. In what follows, we will show the results achieved by back-simulating one coastal and two completely underwater flow-like landslides:

- The 1997 coastal debris flow at Lake Albano (Rome zone, Italy);
- The 2008 submarine debris flow in the nearshore of Bagnara Calabra (South Italy);
- The 1888 submarine debris flow in the nearshore of the Trondheim harbour(Norway).

Detailed bathymetric data derived by sonar multibeam surveys as well as geological data derived from geophysical and geological surveys were available for the three sites thus allowing a strong control on the achieved results. Note that hydroplaning was not applied in the studied real events, because not relevant (for the considered approximation degree) for their overall phenomenological behaviour.

A quantitative evaluation of simulations results were also performed according to a fitness function based on the areal comparison of real and simulated event (Iovine et al. 2005). The used function is $e = \surd((R \cap S)/(RUS))$, where R is the set of cells involved in the real event and S the set of cells involved in the simulated event. Note that e can range from 0 (total failure) to 1 (perfect simulation).

Lake Albano

The 1997 Lake Albano (Rome, Italy) event (Fig. 1) is a rare case of well constrained combined subaerial-subaqueous debris flow (Mazzanti et al. 2007; Bozzano et al. 2009). This event occurred in the eastern slope of the Lake Albano on the 7th November 1997 after an intense rainfall (128 *mm* in 24 h), and began as a soil slide, mobilizing about 300 m^3 of eluvial material. The mobilized mass was channelled within a steeply dipping impluvium (about 40°) entraining a large amount of debris material along the bottom of the channel and thus reaching an estimated volume of some thousands of m^3 at the coastline. A few amount of material was deposited at the coastline, while a greater quantity entered in water generating a little tsunami wave. Numerical Simulation by SCIDDICA-SS2 model was performed by using a 1 m resolution DTLM (Digital Terrain and Lacustrine Model) derived from an aerial LiDAR survey and a sonar multibeam bathymetric survey. Geomorphological

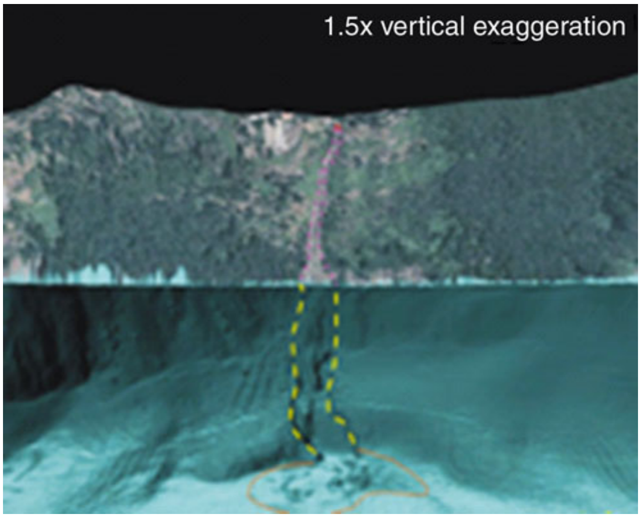

Fig. 1 The 1997 Albano lake subaerial-subaqueous debris flow

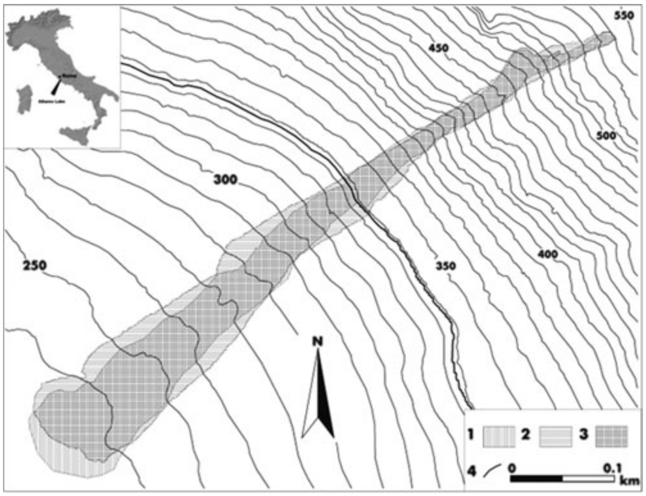

Fig. 2 The 1997 Albano lake subaerial-subaqueous debris flow as simulated by the SCIDDICA-SS2 model. Key: (*1*) real event, (*2*) simulated event, (*3*) intersection between real and simulated event, (*4*) water level

interpretation of the real event was performed by using multi-temporal aerial photos for the subaerial part of the slope and high resolution bathymetry for the submerged part. Geological and geotechnical parameters were also determined by dedicated field surveys.

Subsequently, the real event was back analysed by the SCIDDICA-SS2 model thus achieving a quite satisfactory result in terms of fitness function (Fig. 2). A value of *e* of 0.85 was obtained for the aerial path (Avolio et al. 2008). Furthermore, results show a good agreement also in terms of erosion and deposits on both subaerial and subaqueous parts. Landslide velocities ranging from 0 to 15 *m/s* were found with a peak at the coastline. Values lower than 12–13 m/s were recorded in the submerged part (Fig. 3).

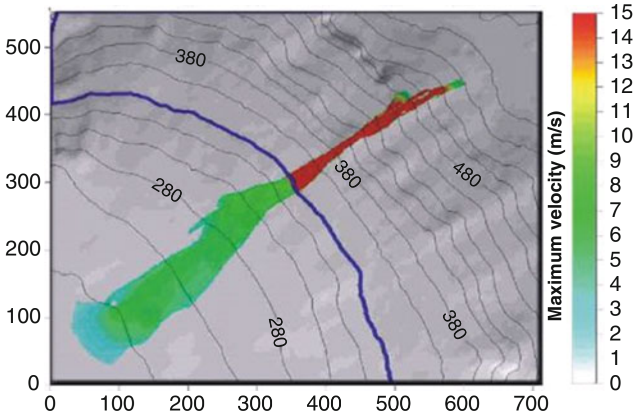

Fig. 3 Maximum velocity computed during the entire simulation of the Albano landslide

The 1997 debris flow at Lake Albano has been recently simulated also by the DAN3D model (McDougall and Hungr 2004) using the EFEM approach (Mazzanti and Bozzano 2009).

Achieved results are very similar to those obtained by SCIDDICA-SS2. Furthermore, SCIDDICA demonstrated to be more efficient in some respects like:

- Simulation of two or more niches along the path;
- Seabed erosion directly computed by the model (and not imposed at the beginning like in DAN3D);
- Better management of the air to water transition.

Further details can be found in Mazzanti et al. 2009.

Bagnara Calabra

A completely submarine landslide was detected in the near-shore of Bagnara Calabra (Italy) by comparing detailed bathymetries coming from two sonar multibeam surveys carried out in November 2007 and in September 2008. Landslide detachment area was located between 10 and 20 *m* b.s.l., about 100 *m* far from the coastline. Initial landslide volume was also estimated at about 16,000 m^3 with a maximum thickness of 9 *m*. Erosion up to 4 *m* has been recorded along the pathway between 20 and 60 *m* b.s.l.. Final deposits are partly distributed between 60 and 90 *m* b.s.l. and partly below 100 *m* with a maximum thickness of 5 *m*.

The landslide was simulated by the SCIDDICA-SS2 model and a fitness value of 0.85 was achieved (Avolio et al. 2009). Furthermore, deposit and erosion locations in the simulation agree very satisfactorily with the real event; moreover, deposit thickness and erosion depth values do not differ substantially (Fig. 4). The detachment area was completely emptied after about 1 min and the flow propagated until its final position in few minutes. Landslide velocity was up to 6 m/s in the upper part of the slope, immediately after the mass release, and dropping below

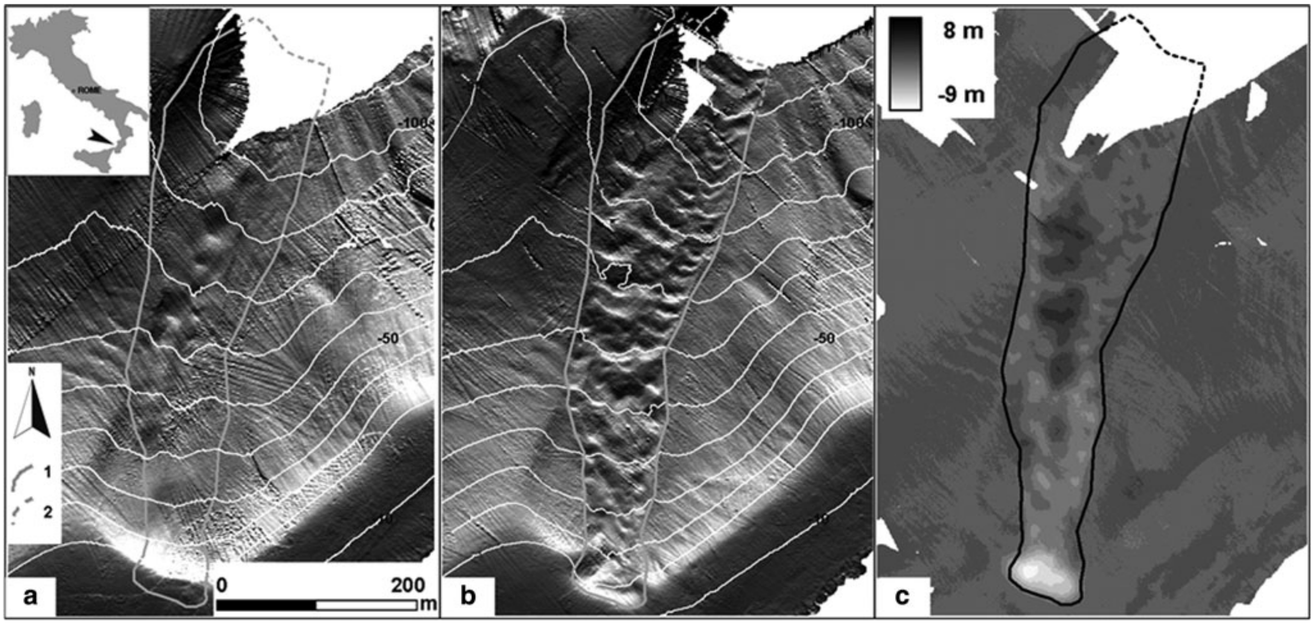

Fig. 4 (**a**) Shaded relief of the pre-landslide bathymetry; (**b**) shaded relief of the post- landslide bathymetry; (**c**) residual between the pre- and the post- landslide bathymetry (missing data areas are in *white*); lines superimposed to contours identify: (*1*) perimeter of real event, (*2*) probable real event perimeter in missing data area

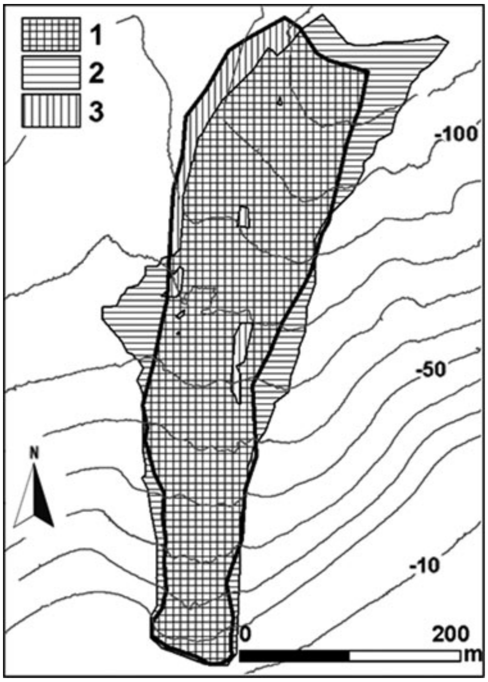

Fig. 5 Simulation of Bagnara subaqueous landslide. Intersection between real and simulated event: (*1*) intersection; (*2*) only simulated (*3*) only real

4 m/s in the following stages. Such values of velocity may be considered reasonable according to analyses of main characteristics of the event (type and volume of landslide, slope gradient up to 12°, etc.) and indicative results of subsequent approximate calculations (De Blasio 2011). Figure 5 shows the simulation of Bagnara subaqueous landslide obtained by SCIDDICA-SS2.

Trondheim

Nearshore landslides in the bay of Trondheim have been recorded since the XIX century, such as the 1888 landslide and tsunami. The most dangerous landslide occurred on April 23rd, 1888, and was accompanied by a 5–7 m high tsunami, that killed one person and caused major damage to port facilities (L'Heureux et al. 2010 and references therein).

Recent studies provide detailed information about the morphology of the seafloor and landslide mechanisms (L'Heureux et al. 2010). Geomorphological data suggest an offshore detachment along a weak clayey sediment layer and consequent retrogression across the shoreline. Due to the deltaic nature of sediments involved, the landslide transformed rapidly into a DF, that propagated along the Nidelva channel reaching a distance of about 3–4 km from the coastline at a water depth of about 400 m. Seabed erosion along the pathway triggered slope failures on the flanks of the channel, thus increasing the total amount of involved material. Following L'Heureux et al. 2010, the largest landslide along the flanks of the Nidelva channel (named W-landslide) was triggered 2 km off-shore at a water depth of 80–160 *m*.; its total volume can be estimated to ~$1.45 \times 10^6\ m^3$.

Aiming at better understanding the complex behaviour of this landslide, preliminary numerical simulation using SCIDICASS2 has been performed. The landslide was simulated by accounting for an initial progressive failure of the scar (trying to simulate the retrogressive behaviour of the landslide) and then propagating as a debris-flow. In the simulation W-landslide has been triggered by the transit and erosion at the toe. The simulated path of the landslide was compared with the one suggested by L'Heureux et al. 2010, thus obtaining a fitness function value close to 0.73.

Conclusions

SCIDDICA-SS2 is a powerful model for simulating submarine landslides. Several peculiar features make it suitable for the simulation of events characterized by different features. First of all submarine landslides initiated in a subaerial slope can be simulated in a rigorous way. Furthermore, the management of secondary landslides triggered along the path allows to properly simulate events like the 1997 Lake Albano and 1888 Trondheim debris-flows. Moreover, SCIDDICA-SS2 showed its effectiveness in simulating flow-like landslides both on open slopes and on narrow and complex channels. Several outputs can be obtained by SCIDDICA-SS2 such as the area affected by the landslides, the erosion along the path, the thickness of the mass and velocity. These data can be very useful in back analysing past landslides and their induced effects (i.e. tsunamis); however, if a suitable calibration is carried out, different scenarios based on the analysis for future events can also be performed. Hence, SCIDDICA-SS2 can be used for assessing the risk related to future events and for designing possible countermeasures.

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