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A Cellular Automata Model for Flow-like Landslides with Numerical Simulations of Subaerial and Subaqueous Cases

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Abstract

Numerical modelling is a major challenge in the prevention of risks related to the occurrence of subaerial and subaqueous landslides. SCIDDICA-SS2 and SCIDDICA-SS2blocks are Macroscopic Cellular Automata models, developed for the simulations of combined subaerial-subaqueous flow-like landslides. SCIDDICA-SS2 was firstly validated on the 1997 subaerial - subaqueous debris flow at Lake Albano (Rome, Italy). This paper outlines the last version of the model, slightly improved and which was extended in order to simulate landslide characterized by large blocks inside the main landslide debris. The paper presents applications of the model to a completely submarine landslide, occurred between November 2007 and September 2008, in the nearshore of Bagnara Calabra town (Italy) and to the catastrophic M. Pacì rock-avalanche occurred on February 6, 1783 (Scilla, Italy). Simulation results of Bagnara Calabra submarine landslide by SCIDDICA-SS2 show a strong convergence between the real and simulated areas affected by the event. Furthermore, numerical analyses by SCIDDICA-SS2blocks demonstrate the ability of the model to simulate rock avalanches characterized by large blocks.

Keywords: *Modelling and Simulation, Cellular Automata, Debris Flow, Rock Avalanche, Subaqueous Landslide*

1. Introduction

Cellular Automata (CA) represent a parallel computing paradigm for modelling and simulating complex dynamical systems, whose evolution is mainly based on local interactions of their constituent parts (Chopard and Droz, 1998). Many complex fluid-dynamical phenomena are modelled by CA: the lattice Boltzmann method covers a large class of such phenomena, mostly at a mesoscopic and microscopic level (Chopard and Droz, 1998). An extension of the CA paradigm for macroscopic systems and a related modelling methodology were established in order to simulate also fluid-dynamical phenomena (Di Gregorio and Serra, 1999). Good simulation results were obtained for some types of "macroscopic" surface flows: lava flows and pyroclastic flows for volcanic eruptions, debris, mud, granular flows for landslides with the SCIARA, PYR, and SCIDDICA (Avolio et al., 2003) models, respectively.
These families of models have been developed according to an incremental strategy, permitted by the CA features. Initially, the model considers only fixed basic characteristic of the phenomenon; real cases, whose evolution doesn't depend decisively on other characteristics, are selected for the validation purposes. This permits to initiate the first model of the family for less complex cases; new versions will be generated step by step by introducing other features which control the analysed phenomenon occurring in other real cases. The more recent versions cover larger classes of the phenomenon both for the back-simulation of past events and for hazard assessment by forecasting the evolution of in progress or future events. Furthermore, this type of numerical analysis can also allow to test the effects of protection works.
Flow-like landslides are complex dynamical systems: the phenomenon usually starts from rock or soil detachments, that originate debris, mud or granular flows, whose rheological properties may change during

evolution by water loss or inclusion. Furthermore, flow-like landslide are usually characterized by soil surface erosion and in some cases by secondary sources activation and with consequently entrainment of material. In the case of flow-like landslides occurring in coastal regions an air to water transition must be also considered which can lead to different processes: impulsive loss of matter (water and finer grains) and energy dissipation at the impact. Moreover, buoyancy effect, drag force and peculiar mechanisms like hydroplaning play a significant role in the submerged path.

The first release "T" of SCIDDICA was a simple CA model with purely gravitational flows and was validated on the Tessina earth flow, characterised by a velocity up to few meters per day (Avolio et al., 2000). The release "O", applied to the Mt. Ontake debris avalanche (1984, Japan) is a crucial extension of the basic T-model: the considered landslide was extremely rapid (20–26 m/s) and thus characterised by relevant run-up effects (Di Gregorio et al., 1999). The successive releases "Sx" of SCIDDICA were developed for simulating debris flows, which were characterised also by strong soil erosion along the landslide path; they were validated on the Sarno (1998, Italy) debris flows (D'Ambrosio et al., 2003, 2006, 2007) with various improvements concerning inertial effects and then applied to other similar landslides (Iovine et al., 2003).

Other old and new CA models for landslides have to be mentioned because of their relevance.

Segre and Deangeli (1995) presented a three-dimensional numerical model, based on CA, for debris flows, adopting empirical flow laws based on difference equations. The model was validated on the M. XiKou landslide (China, 1989) capturing its main characteristics.

Clerici and Perego (2000) simulated the Corniglio landslide (1994-1996, Italy) using a simple CA model in order to capture the blockage mechanisms for that type of landslide.

Salles et al. (2007) recently developed an interesting CA model for subaqueous flows, in order to simulate density currents. Their approach is similar to SCIDDICA and results concerning real cases are remarkable.

The last challenge concerned SCIDDICA-SS2, that is an extension to combined subaerial - subaqueous flow-like landslides with a new flows characterization by their mass centre position and velocity (Avolio et al., 2008); the extremely accurate investigation of the 1997 Lake Albano (Italy) subaerial – subaqueous debris flow (Mazzanti et al., 2007) permitted to validate the model and to compare this CA simulator with other simulators based on differential equations systems (Mazzanti et al., 2009). The version SCIDDICA-SS2blocks, here presented, includes SCIDDICA-SS2 and is mainly improved by introducing blocks and their interaction with the main debris.

The model SCIDDICA-SS2blocks is presented in the next section, while the simulation results concerning the submarine landslide in the nearshore of Bagnara Calabra town and coastal M. Pacì catastrophic rock-avalanche are shown in the third section, a short discussion concludes the paper.

2. SCIDDICA-SS2 and SCIDDICA-SS2blocks Models for Flow-like Landslides

A CA evolves in a discrete space-time. Space is partitioned in cells of uniform size, each cells embeds a Finite Automaton (FA) computing unit, that changes the cell state according to the states of the neighbour cells, where the neighbourhood conditions are determined by a pattern invariant in time and space.

The cell state for macroscopic phenomena is expressed by substates, that individuate all the (physical, chemical, biological etc.) characteristics, relevant to the system evolution and related to the space portion corresponding to the cell. At first, cells are in arbitrary states and describe the initial conditions of the system; the Cellular Automaton evolves changing the state of all the cells simultaneously at discrete times (CA step), in accordance with the FA transition function. It may be decomposed for macroscopic CA in a sequence of "elementary" processes, each one updating CA states. In the case of surface flows, quantities concerning the third dimension, (e.g., altitude, debris thickness, kinetic head) may be easily included among the CA substates, permitting models in two dimensions, working effectively in three dimensions.

2.1 Formal Definition of Model SCIDDICA-SS2blocks

SCIDDICA-SS2blocks is a deterministic two dimensional CA with regular hexagonal cells for simulating subaerial-subaqueous flow-type landslides with large blocks inside. It includes progressive detachment for primary and secondary sources, surface erosion, matter loss and rheological changes in the water transition. It is specified by the quintuple:

$$<R, X, S, P, \tau>$$

• ***R*** is the set of regular hexagons, that cover the region, where the phenomenon evolves.

• $X = X_f \cup X_m$ identifies the geometrical pattern of cells, which influence any state change of the generic cell, identified as the central cell: X_f includes the central cell itself (index 0) and the six adjacent cells (indexes 1, ... ,6) and represents the maximum flow range; the blocks are rigid bodies, whose extension covers many cells, they are idealised as cylinders with a maximum possible radius ***r***, related to the features of the landslide, X_m includes all the possible cells occupied by a block of maximum size plus the external adjacent cells, when the centre of the largest block is situated in the central cell.

• ***S*** is the set of FA states, they are specified by soil substates, flows substates and blocks substates.

Soil substates: ***A*** is the cell altitude, ***D*** is the depth of soil erodable stratum, that could be transformed by erosion in landslide matter; ***TH*** is the average thickness of landslide matter of the cell, ***X*** and ***Y*** are the co-ordinates of its barycentre with reference to the cell centre, ***KH*** is its kinetic head.

Flow substates: ***E*** is the part of flow, the so called "external flow" (normalised to a thickness), that penetrates the adjacent cell from central cell, ***XE*** and ***YE*** are the co-ordinates of its barycentre with reference to the adjacent cell centre, ***KHE*** is its kinetic head, (six components for each substate); ***I*** is the part of flow toward the adjacent cell, the so called "internal flow", (normalised to a thickness) that remains inside the central cell, ***XI*** and ***YI*** are the co-ordinates of its barycentre with reference to the central cell centre, ***KHI*** is its kinetic head, (six components for all the substates).

Megablocks substates: ***MTH*** is the megablock constant thickness, ***MR*** is its radius, ***XD***, ***YD*** are the ***x***, ***y*** distances from the megablock centre, ***SLX***, ***SLY*** individuate the megablock slope, ***MVX***, ***MVY*** are the speed components of megablock, ***MI*** is the identification number of the megablock.

• ***P*** is the set of the global physical and empirical parameters of the phenomenon, they are enumerated in the following list and are better explicated in next section:

a is the cell apothem; ***t*** is the temporal correspondence of a CA step; adh_w, adh_a are the water/air adhesion values, i.e. the landslide matter thickness, that may not removed; fc_w, fc_a are the water/air friction coefficient for the landslide matter outflows; td_w, td_a, ed_w, ed_a are water/air parameters for energy dissipation by turbulence, water/air parameters for energy dissipation by erosion; ***ml*** is the matter loss in percentage when the landslide matter enters into water; mt_w, mt_a are the water/air activation thresholds of the mobilisation; ***tmt*** is the activation threshold of the mobilisation for the transept; er_w, er_a are the water/air progressive erosion parameters; ***wr*** is the water resistance parameter; fcm_w, fcm_a are the water/air friction coefficient for the megablocks; ***mwr*** is the water resistance parameter for megablocks.

• τ: $S^n \rightarrow S$ is the deterministic state transition for the cells in ***R***, where ***n*** is the cardinality of *X*. Basic elements of the transition function will be sketched in the next section.

At the beginning of the simulation, we specify the states of the cells in ***R***, defining the initial CA configuration. The initial values of the substates are accordingly initialised. In particular, ***A*** assumes the morphology values except for the detachment area, where the thickness of the landslide mass is subtracted from the morphology value; ***TH*** is zero everywhere except for the detachment area, where the thickness of landslide mass is specified; ***D*** assumes initial values corresponding to the maximum depth of the mantle of soil cover, which can be eroded; at the beginning, megablocks are considered as buried in some cells of the detachment area, where their substates are opportunely initialized and no further division process is considered. All the values related to the remaining substates are zero everywhere.

At each next step, the function τ is applied to all the cells in $\boldsymbol{R}$, so that the configuration changes in time and the CA evolution is obtained.

2.2 The transition function of the model SCIDDICA-SS2blocks

Five local processes may be considered for the release SS2blocks of SCIDDICA:

- altitude, kinetic head and debris thickness variation by detrital cover mobilisation;
- kinetic head variation by turbulence dissipation;
- debris outflows (thickness, barycentre co-ordinates, kinetic head) determination and their shift deduced by the motion equations;
- composition of debris inside the cell (remaining debris more inflows) and determination of new thickness, barycentre co-ordinates, kinetic head;
- block movements.

In the following, a sketch of the local elementary processes will be given, which is sufficient to capture the mechanisms of the transition function; the execution of an elementary process updates the substates. When substates need the specification of the neighbourhood cell, its index is indicated between square brackets. $\Delta \boldsymbol{Q}$ means variation of the substate $\boldsymbol{Q}$; the subscripts "$\boldsymbol{w}$" and "$\boldsymbol{a}$" in parameter names are omitted, when the formula is considered valid both in water and air.

Mobilisation Effects. When the kinetic head value overcomes an opportune threshold ($\boldsymbol{KH>mt}$), depending on the soil features and its saturation state, a mobilisation of the detrital cover occurs proportionally to the quantity overcoming the threshold: $\boldsymbol{er\cdot(KH\text{-}mt)=\Delta TH=\text{-}\Delta D}$ (the detrital cover depth diminishes as the debris thickness increases), the kinetic head loss is: $\boldsymbol{\text{-}\Delta KH=ed\cdot(KH\text{-}mt)}$. The mixing of the eroded detrital cover with the earlier debris involves that the earlier debris kinetic energy becomes the kinetic energy of all the mass of debris, trivially implicating a further kinetic head reduction.

The activation of secondary sources along the landslide path is managed by utilising a ''transept'' for each secondary source. A threshold $\boldsymbol{tmt}$ for the thickness of the debris flow crossing the transept is specified and secondary soil slips are activated for $\boldsymbol{TH>tmt}$.

Turbulence Effect. The effect of the turbulence is modelled by a proportional kinetic head loss at each SCIDDICA step: $\boldsymbol{\text{-}\Delta KH=td\cdot KH}$. This formula involves that a velocity limit is imposed de facto. A generic case with a maximum value of slope may be always transformed in the worst case of an endless channel with constant maximum value slope. In this case, an asymptotic value of kinetic head is implied by infinite formula applications and, therefore, a velocity limit is deduced. This effect can simulate both turbulence effect in the flowing mass and, in the submerged path, drag forces under high values of Reynolds number.

Debris Outflows. Outflows computation is performed in two steps: determination of the outflows minimising the "height" differences in the neighbourhood (Di Gregorio and Serra, 1999) and determination of the shift of the outflows. The minimisation algorithm defines a central cell quantity $\boldsymbol{d}$ to be distributed $\boldsymbol{d=\Sigma f[i]}$ $\boldsymbol{0\leq i\leq 6}$, where $\boldsymbol{f[i]}$ is the flow towards the cell $\boldsymbol{i}$ ($\boldsymbol{f[0]}$ is the part of $\boldsymbol{d}$, which remains in the central cell); $\boldsymbol{h[i]}$, $\boldsymbol{0\leq i\leq 6}$ are the quantities that specify the "height" of the cells in the neighbourhood, to be minimised by contribution of flows: more precisely, the algorithm minimises the expression:

$$\boldsymbol{\Sigma\, (|(h[i]+f[i]) - (h[j]+f[j])|)} \text{ for } \boldsymbol{\{(i,j) \mid 0\leq i<j\leq 6\}}.$$

"Height" is specified in different ways according to the features of the phenomenon. Rapid flows imply often a run up effect, depending on the associated kinetic head, furthermore an adherence must be defined, i.e. the thickness of matter, that cannot be removed from the basal surface.

As a consequence, for the central cell $\boldsymbol{0}$ $\boldsymbol{d=TH[0]\text{-}adh}$ and $\boldsymbol{h[0]=A[0]+KH[0]+adh}$, while for the adjacent cells $\boldsymbol{h[i]=A[i]+TH[i]}$, $\boldsymbol{1\leq i\leq 6}$; note that $\boldsymbol{KH[0]}$ accounts for the ability of the flows from the central cell of climbing a slope.

The barycentre co-ordinates x and y of moving quantities are the same of all the matter inside the cell and the form is ideally a "cylinder" tangent the next edge of the hexagonal cell. A preliminary test is executed in order to account for the friction effects, that prevent debris outflows, when the slope "$\theta[i]$" between the two cells **0** and i (it is determined by the height difference $h[0]+d-h[i]$) is such that that $tan\theta[i]<fc$.
A ideal distance "***dist***" is considered between the central cell debris barycentre and the centre of the adjacent cell i including the slope $\theta[i]$.
The $f[i]$ shift "***sh***" is computed for subaerial debris flow according to the following simple formula, that averages the movement of all the mass as the barycentre movement of a body on a constant slope with a constant friction coefficient: $sh=v\cdot t+g\cdot(sin\theta-fca\cdot cos\theta)\cdot t^2/2$, with "$g$" the gravity acceleration and initial velocity $v=\sqrt{(2g\cdot HK)}$. The shift formula for subaqueous debris considers also the water resistance, using modified Stokes equations with a form factor proportional to mass and $g'<g$, accounting for buoyancy: $sh=(1-exp(-wr\cdot t))(v-(g'\cdot(sin\theta-fcw\cdot cos\theta)/wr))+g'\cdot(sin\theta-fcw\cdot cos\theta)\cdot t/wr$.
The motion involves three possibilities: (1) only internal flow, the shifted cylinder is completely internal to the central cell; (2) only external flow, all the shifted cylinder is external to the central cell inside the adjacent cell; (3) the shifted cylinder is partially internal to the central cell, partially external to the central cell, the flow is divided between the central and the adjacent cell, forming two cylinders with barycentre corresponding to the barycentre of the internal flow and the external flow. The kinetic head variation is computed according to the new position of internal and external flows, while the energy dissipation was considered as a turbulence effect in the previous elementary process.
Flows Composition. When debris outflows are computed, the new situation involves that external flows leave the cell, internal flows remain in the cell with different co-ordinates and inflows (trivially derived by the values of external flows of neighbour cells) could exist. The new value of ***TH*** is given, considering the balance of inflows and outflows with the remaining debris in the cell. A kinetic energy reduction is considered by loss of flows, while an increase is given by inflows: the new value of the kinetic head is deduced from the computed kinetic energy. The co-ordinates determination is calculated as the average weight of co-ordinates x and y considering the remaining debris in the central cell, the internal flows and the inflows.
Air-Water Interface. Air-water interface is managed only for external flows from air to water. An external flow from an air cell (altitude higher than water level) to a water cell (altitude lower than water level) can imply a loss of matter (water inside debris and fine grains) proportional to debris mass, specified by ***ml***; it implies a correspondent loss of kinetic energy, determined by kinetic head decrease.
Block movements. A block is modelled to move as a rigid body along the line of maximum slope when there is no fluid matter in all the cells or in part of the cells occupied by it; the shift of blocks is computed by opportune motion equations. The fluid matter "sees" the block as solid soil in this case. A block is modelled to move as a floating body when there is fluid matter in all the cells occupied by it; shift of blocks is deduced by the total matter movement (as fluid movement) for cells, where the block exists. A further shift of blocks is computed, if collisions among blocks occur.

3. Model Application to Two Coastal and Submerged Flow-like Landslides in Calabria

3.1 The 2007 Submarine Landslide in the Nearshore of Bagnara Calabra (Italy)

A completely submarine landslide was detected in the nearshore of Bagnara Calabra (fig.1) by comparing detailed bathymetries coming from two sonar multibeam surveys carried out in November 2007 and in September 2008 for the PRIN 2006042319 project on innovative techniques for coastal landslides studies

(Bosman, 2009). The few centimetres resolution of bathymetric data allowed to recognize the landslide detachment between 10 m and 20 m b.s.l., about 100 m far from the coastline.
The surveys didn't completely cover the area of final part of the landslide, however, such partial data can be considered more than sufficient for a first broad and in-depth analysis.
Initial landslide volume was also estimated at about 16.000 m^3 with a maximum thickness of 9 meters. Erosion up to 4 m has been recorded along the pathway between 20 m and 60 m b.s.l.. Final deposit is partly distributed between 60 m and 90 m b.s.l. and partly below 100 m with a maximum thickness of 5 m.
A first evaluation of simulation was performed by areal comparison of real and simulated event according to a standard fitness function (D'Ambrosio and Spataro, 2007): $\sqrt{((\boldsymbol{R} \cap \boldsymbol{S})/(\boldsymbol{R} \cup \boldsymbol{S}))}$, where $\boldsymbol{R}$ is the set of cells involved in the real event, $\boldsymbol{S}$ is the set of cells involved in the simulated event. A value between 1 (perfect simulation) and 0 (simulation total failure) is obtained, values larger than 0.7 may be considered satisfying for landslide simulations. A good value of 0.85 was achieved for the Bagnara Calabra submarine landslide. 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.2).
The detachment area was completely emptied after about one minute and the flow propagates 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 then they dropped below 4 m/s in the following stages. Such values of velocity are considered reasonable for the type and volume of landslide and the slope gradient (up to 12°).

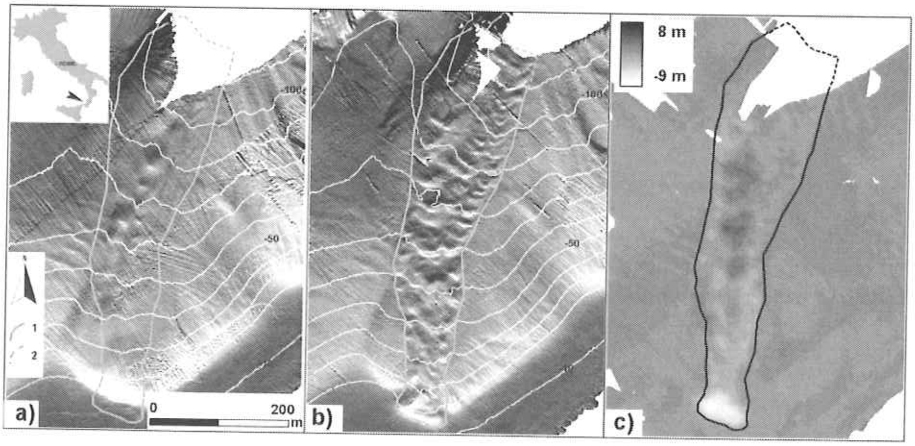

Figure 1: a) shaded relief of the pre-landslide bathymetry; b) shaded relief of the post- landslide bathymetry; c) residual between the pre- and the post- landslide bathymetry (missing data areas are in white); contour lines are referred to: 1 perimeter of real event, 2 probable real event perimeter in missing data area

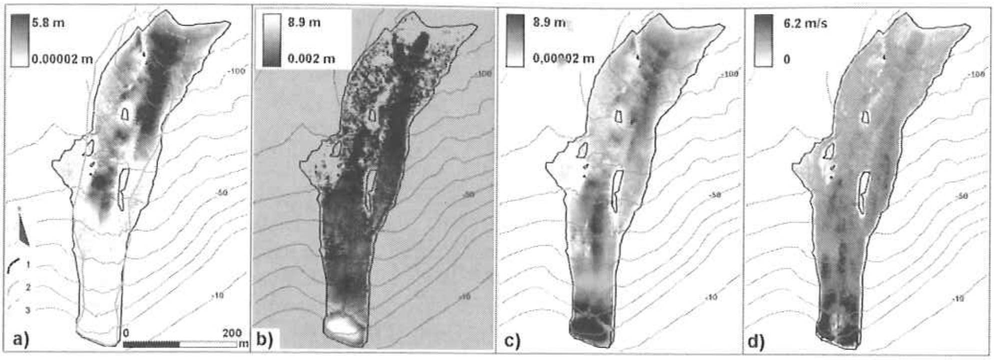

Figure 2: simulation of Bagnara Calabra subaqueous landslide a) deposit thickness, b) erosion, c) maximum occurred debris thickness; d) maximum occurred velocity; contour lines are referred to: 1 perimeter of the simulated event; 2 perimeter of real event; 3 probable real event perimeter in missing data area.

3.2 Reconstruction of the 1783 M. Pacì catastrophic coastal rock-avalanche

Between February 5th and March 28, 1783, Southern Calabria (Italy) was struck by an exceptionally violent seismic sequence, with five main shocks between M5.8 and M7.3. Several landslide was induced by the earthquakes that are well described in the historical sources. One of the main landslide occurred on the coast just south of the Scilla town (Bozzano et al., 2008). Historical witnesses report that some 30 after minutes after the February 6^{th} earthquake (occurred shortly after midnight) part of the seaward flank of Pacì Mountain collapsed. Immediately afterwards a tsunami wave was generated, that killed some 1500 people that were camping on the neighbour beach (Marina Grande) because of the previous day's earthquake.
Detailed subaerial and submarine investigations and studies have been recently carried out with the aim of better characterize one of the most catastrophic landslides historically reported in Italy (Bozzano et al., 2008; Mazzanti, 2008).

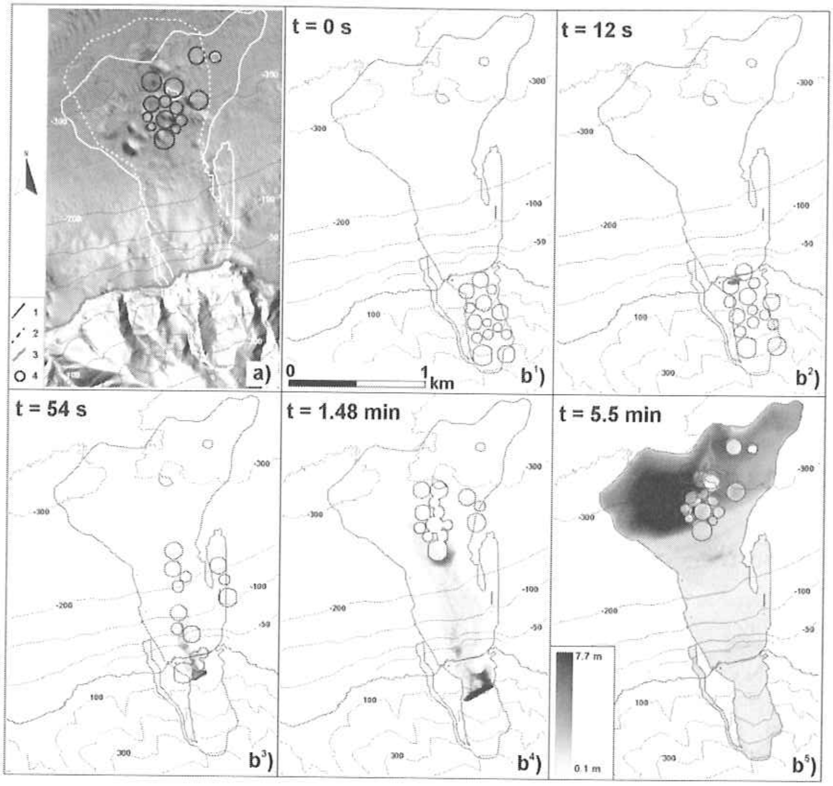

Figure 3: Simulation of the 1783 M. Pacì rock avalanche a) shaded relief of subaerial and subaquoeus area with simulated event contour line 1, real event contour line 2, water's edge line 3, rock blocks 4; b) debris thickness during the landslide evolution at 0s (b¹), 12s (b²), 54s (b³), 1,48m (b⁴), 5,5 m (b⁵).

The landslide, which involved a total volume of about $5 \cdot 10^6$ m^3, was classified as a rock-avalanche. A submarine deposit, featured by several blocks as large as $2 \cdot 10^5$ m^3, was recognized at about 1.2 - 1.7 km far from the coastline.

Due to the presence of large blocks the landslide was simulated by both SCIDDICA SS2 and SCIDDICA SS2blocks, the last one specifically developed for such a type of phenomena. Simulation by SCIDDICA SS2 involves the simplification of not accounting for the presence of blocks while simulation by SCIDDICA SS2blocks involves simplifications in defining initial conditions of blocks like: a) dynamic fragmentation during the propagation was not taken into account and blocks were considered already in their final dimensions; b) geometry of blocks was idealised as cylinders which in the initial stage of the simulation was buried in the landslide matrix; c) interaction between the blocks and the debris is simulated in a very simple and straightforward way.

Since the original disposal of blocks in the landslide source cannot be inferred by any type of analysis, many different hypotheses may be put forward; therefore, many simulations were performed according to different initial conditions. Best results was achieved by using the release SS2blocks of the SCIDDICA code thus demonstrating the importance of considering the presence of large blocks in simulating such a type of landslides. Figure 3 shows such a simulation, where final position of blocks in the simulation agrees approximately with the real event. The fitness function for areal comparison between the real simulated event reports a satisfying value of 0.81.

4. Conclusions

SCIDDICA SS2 and its improved version SS2blocks are advanced cellular automata models for the numerical simulation of completely subaerial, completely submerged or combined flow-like landslides. SCIDDICA SS2blocks has been specifically developed for simulating flow-like landslides characterized by large blocks such as rock-avalanches or debris-avalanches.

A first validation of SS2 version for completely submerged landslides has been here presented by simulating the submerged mass movement which affected the nearshore of Bagnara Calabra in 2007/2008.

Good results have been achieved by back-analysing this event. This is a very interesting case study since, thanks to the very accurate pre and post-landslide bathymetry, it allowed for a precise validation of the simulation results. Moreover, it permitted some improvements and reflections in kinetic head management and detachment phase. In spite of its limited size this type of events must be taken into account in the frame of hazard management in coastal areas due to their high frequency of occurrence.

On the opposite, events like the 1783 Scilla rock-avalanche represent a quite serious threat for costal communities due to their large volume and the related tsunamigenic potential. However, this type of mass movements are very complex to be simulated due to the complexity of mechanisms controlling their propagation after the failure. The solution to simulate the presence of large blocks was found by cleverly coupling two CA, one for fluid matter and another one for rigid bodies. Of course, the breaking phase is not modelled and blocks are "buried" in the detachment area. Back-analysis simulation of the well constrained 1783 Scilla landslide has given satisfying results in terms of areal fitting and blocks distribution. However, some limitations have been recognized in such as the mechanism of initial mass release and the momentum management; these features will represent future improvement of the model.

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