

DEBRIS FLOWS SIMULATION BY CELLULAR AUTOMATA: A SHORT REVIEW OF THE SCIDDICA MODELS

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ABSTRACT

Cellular Automata models are a promising solution for the simulation of debris flows moving over a 3D topography. In this paper, an extensive review of SCIDDICA, a Cellular Automata model based on the equivalent fluid approach, is presented. Moreover, the main steps in the development of SCIDDICA are described with a chronological criterion. The last version of SCIDDICA (SS2) is suitable for the simulation of completely subaerial, completely subaqueous and combined subaerial-subaqueous debris flows. Main features of a debris flow are accounted by the SS2 version such as erosion and deposition and triggering of secondary landslides along the path, presence of structures and buildings, run-up effects and, in the case of coastal landslides, impulsive loss of matter (water and finer grains) and energy dissipation at water impact. Moreover, buoyancy effects, drag forces and peculiar mechanisms like hydroplaning are also modeled for submerged events. Several past debris-flows like the 1998-1999 Campanian debris flows (Italy), the 1997 debris flow at Lake Albano (Italy) and the 2008 submarine debris flow at Bagnara Calabria (Italy) have been simulated in the last years by SCIDDICA. A short review of these case studies will be presented and the main limitations encountered will be also discussed, thus suggesting future improvements and perspectives, such as susceptibility analysis and interaction with man made structures

KEY WORDS: debris flows, modelling & simulation, cellular automata, susceptibility analysis

INTRODUCTION

Numerical modeling is a major challenge in the prevention of risks related to the occurrence of landslides. Debris flows (DF) (IVERSON, 1997; HUNGR *et alii*, 2001) are one of the most common and dangerous types of landslides and may be classified as complex systems of fluid-dynamical type. DF are extremely rapid channeled landslides, composed of slurry of rock, mud, organic matter and water, usually originated by soil detachments in relation with intense rainfalls, snow melt etc. DF may occur in subaerial, subaqueous or mixed environment and their size can vary from 10^2 to 10^9 m³ (JAKOB, 2005). Nevertheless, the final volume of a DF is significantly larger than the detached volume (also 100 times larger) due to the erosion and consequent entrainment of material along the path (HUNGR *et alii*, 2005). Furthermore, in some cases the intense erosion can trigger secondary landslides along the channel, thus furtherly increasing the final volume of mobilized material. Hence, rheological properties (MAJOR & PIERSON, 1992) of initial heterogeneous mixture of soil and water may change during propagation by water loss or inclusion. Additional mechanisms, such as impulsive loss of matter (water and finer grains) and energy dissipation at impact, must be considered in the cases of coastal DF. Differently, buoyancy effects, drag forces and peculiar

mechanisms like hydroplaning play a significant role in the submerged path.

The aforementioned features cannot be neglected in the numerical simulation of a DF. However, many problems arise due to the extreme complexity of these events, which lead to difficulties in estimating kinematic geotechnical soil parameters for real phenomena (ANCEY, 2007). These features may be approximately described in terms of fluid-dynamics by PDE (partial differential equations), and several models have been developed in the last years by using this approach (HUNGR, 1995; DENLINGER & IVERSON, 2001; McDUGALL & HUNGR, 2004; PIRULLI & MARCO, 2010).

A different methodology to approximately describe and model the main features of a debris flow is represented by MCA (Macroscopic Cellular Automata). MCA are an extension of classical Cellular Automata (CA), developed for overcoming some of the limitation affecting conventional CA frames such as the modeling of large scale complex phenomena. Due to its particulate nature and local dynamics, MCA are very powerful in dealing with complex boundaries, incorporating of microscopic interactions, and parallelization of the algorithm.

CA models for DF are based on the principle of the equivalent fluid, formalized by HUNGR (1995), stating that: “the flowing mass behaves like a fluid, whose rheological features cannot be measured through laboratory or in situ testing, but can only be obtained by the back-analysis of real past events”.

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 alii*, 1982). Since then, MCA were adopted for the simulation of diverse natural phenomena: pyroclastic flows (AVOLIO *et alii*, 2006a), snow avalanches (BARPI *et alii*, 2007; AVOLIO *et al.*, 2010b) and, in particular, flow type landslides (SEGRE & DEANGELI 1995; CLERICI & PEREGO, 2000; AVOLIO *et alii*, 2010a). Among existing Cellular Automata models, we will focus on SCIDDICA, a family of deterministic MCA models, specifically developed for simulating debris flows. 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. Subsequent-

ly, 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 adopted approaches in the most significant models will be given in this paper, together with the results of their application to real cases. However, the detailed description of physical laws controlling the models is not presented in this review paper and we refer to specific references cited in the text for this aspect.

Finally, we will discuss further perspectives of research aimed at improving SCIDDICA and to extend its application to DF analysis.

CELLULAR AUTOMATA: A SHORT OVERVIEW

CA are a paradigm of parallel computing for modelling and simulating complex dynamical systems, whose evolution depends mainly on the local interactions of their constituent parts (e.g. Di Gregorio & Serra, 1999). CA evolves in a discrete space-time context; they are based on a regular division of the space in cells (or, equivalently, a regular lattice, whose sites correspond to the cell centres), each one embedding an input/output computing unit: a finite automaton (fa). S is the finite set of fa states, that the cell may assume. The fa 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. The fa have an identical state transition function, which is simultaneously applied to each cell. At step 0, fa 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 transition function

$$\tau: S^m \rightarrow S,$$

Hence, very complex behaviours can emerge by relatively simple transition functions and few states.

Complex macroscopic phenomena like debris flows need an extension of the original CA definition; Macroscopic Cellular Automata were thus defined in order to fit the modelling requirements of many macroscopic phenomena, from a CA viewpoint, by considering:

- a) the cell dimension, specified by the cell side, and the CA step;
- b) the state of the cell which accounts for several

characteristics that are assumed to be relevant to the evolution of the system (each characteristic corresponds to a sub-state). Moreover, thanks to the sub-state “altitude of the cell” the model can be considered fully 3D.

c) the state transition function τ which must account for all the processes (physical, chemical, etc.) that are assumed to be relevant to the system evolution.

Outflows from the central cell to the other n neighbouring cells must be determined according to the purely local CA approach in order to minimise the differences in “height” in the CA neighbourhood. The general problem may be stated for a generic quantity q according to the following definitions:

- q_d = distributable quantity in the central cell;
- q_0 = not distributable quantity in the central cell;
- q_i = quantity in the cell $i \quad 1 \leq i \leq n$;
- f_0 is the part of q_d remaining in the central cell;
- f_i = flow from the central cell towards the cell $i \quad 1 \leq i \leq n$;
- $q_i = q_i + f_i \quad 0 \leq i \leq n$ with the bound $q_d = \sum_{i=1}^n f_i$
- $0 \leq i \leq n$

The Algorithm for the Minimisation of Differences (AMD) was determined (DI GREGORIO & SERRA, 1999) in order to compute f_i such that the summation of differences among all cells in the neighbourhood $\sum_{\{(i,j) | 0 \leq i, j \leq n\}} (q_i - q_j)^2$ is minimised. A surface flow evolves towards minimum imbalance conditions in “height” at a local level as a “pure” gravitational flow tending to the hydrostatic equilibrium (Avolio et al., 2000). In this framework, run-up effects of flow may be managed by introducing a component of the kinetic head in the “height” of the central cell (e.g., D’AMBROSIO *et alii*, 2003b) while momentum may be managed by an opportune alteration of the “height” in cells along the motion direction (D’AMBROSIO *et alii*, 2006). As a general rule, the dynamics in CA is introduced by relatively simple local laws, observing the conservation laws of physics in an approximation context.

SCIDDICA MODEL: GENERAL FRAMEWORK

The SCIDDICA model can be defined as follows:

$$SCIDDICA = (R, X, S, P, \tau)$$

where:

$$R = \{(x, y) | x, y \in N, 0 \leq x \leq l_x, 0 \leq y \leq l_y\}$$

S_t Altitude of the cell.
S_{TH} Thickness of landslide debris.
S_D Maximum depth of the mantle of detrital cover, that can be transformed by erosion in landslide debris.
$S_D(S)$ Debris outflow (inflows) from the central cell to another neighbor cell; one flow for each direction.
S_E, S_{KE} and S_0 represent respectively the total energy of landslide debris, “kinetic head” and “run-up height” (the height that can be overcome by the debris flow); these sub-states are alternative (one is calculable by other) according to equations, later exhibited.
S_x, S_y Coordinates of the debris barycentre with reference to the cell centre.
$S_{DE}(S_{DE})$ Part of debris flow, the so called “external flow” (“internal flow”), normalised to a thickness, that penetrates the adjacent cell from central cell (that remains inside the central cell); one flow for each direction.
$S_{DE}, S_{DE} (S_{DE}, S_{DE})$ Coordinates of the external flow barycentre (internal flow barycentre) with reference to own cell centre; one for each $S_{DE}(S_{DE})$.
S_{DE}, S_{DE} represent indicators (as velocity is not explicitly) of the momentum of the landslide debris, along the directions x and y , respectively. They are named inertial substates and expressed in terms of momentum.

Tab. 1 - SCIDDICA sub-states.

identifies the co-ordinates of cells, covering the finite region, where the phenomenon evolves (N is the set of natural numbers);

X is the neighbourhood relation (the cell and its adjacent cells), SQ5 and HEX respectively for square and hexagonal tessellation;

S is the finite set of states of the f_a (the list of all sub-states used in the different versions of SCIDDICA is given in Tab. 1);

P is the finite set of parameters (e.g. pap and pt are respectively the cell apothem and the time corresponding to a step of the CA). Specific parameters will be presented in the following sections;

τ is the CA transition function.

In the following, variables concerning sub-states are indicated by their subscripts. When sub-states need the specification of the neighborhood cell, an index at subscript is used. Furthermore, nQ and ΔQ represent, respectively, the new value and variation of the sub-state S_Q .

BASIC ASSUMPTIONS AND INITIAL CONDITIONS

Let us consider a “column” of mass m (with constant density ρ), with base B (the area) and thickness TH at altitude A (cf. example in fig. 1 for hexagonal cells). If g is gravity acceleration, the sub-state total energy, E , is defined as $E = \rho \cdot g \cdot B \cdot TH \cdot (TH/2 + A + KH)$, while the sub-state run-up, R , is defined as $R = TH + KH$. Velocity v is related to KH by $KH = v^2/2g$ (D’AMBROSIO *et alii*, 2003).

Initial conditions are specified by initial values of sub-states:

- S_{TH} is zero everywhere except for the detachment area, where the thickness of landslide mass is

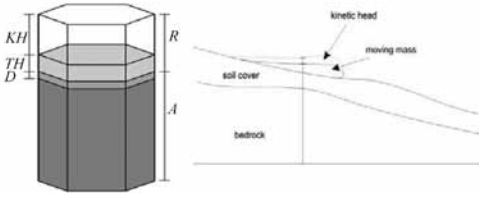


Fig. 1 - 3D visualization of some sub-states for a hexagonal cell together with an ideal section of a debris flow along a slope

specified;

- S_A and S_D are the morphological height and the initial depth of detrital cover, respectively. At this regard must be pointed out that in the case of the detachment area, the thickness of the landslide mass is subtracted from the value of both the morphology and detrital cover;

- S_R coincide with STH debris thickness;

- $E = \rho \cdot g \cdot B \cdot TH \cdot (TH/2 + A)$ (potential energy related to debris mass);

all the values related to the remaining sub-states are zero.

EVOLUTION OF SCIDDICA OVER THE TIME

As discussed above, SCIDDICA has been developed according to an incremental strategy so that the latest versions include all the improvement of previous ones. In the following, a brief review of the evolution of the model in time is presented.

- The first version (**T**) of SCIDDICA was a simple MCA model with purely gravitational flows and it was validated on the 1992 Tessina (Italy) earth flow (AVOLIO *et alii*, 2000), characterised by a velocity up to few meters per day.

In this version X is SQ5, $S = S_A \times S_{TH} \times S_O^4$. AMD is specified by $q_0 = A_0 + adh$, $q_d = TH_0 \cdot adh$, $q_i = A_i + TH_i$, $1 \leq i \leq 4$ (where adh is the adherence parameter, i.e. the thickness of the mud quantity, that becomes adherent to soil). The balance of inflows and outflows in the cells is defined as $nTH_0 = TH_0 + \sum_{1 \leq i \leq 4} (I_i - O_i)$.

- The subsequent version (**O**) was modified in order to simulate extremely rapid landslides characterized by a run up effect, and was tested on the 1984 Mt. Ontake landslide occurred in Japan (DI GREGORIO *et alii*, 1999).

In this version X is SQ5, $S = S_A \times S_{TH} \times S_O^4 \times S_{R_0}$. AMD is specified by $q_d = TH_0 - adh$, $q_0 = A_0 + R_0 \cdot TH_0 + adh$, $q_i = A_i + R_i$, $1 \leq i \leq 4$ and $nTH_0 = TH_0 + \sum_{1 \leq i \leq 4} (I_i - O_i)$. The resulting new run-up is computed by the weighted av-

erage on the thickness for run-up values associated to remaining debris in the central cell plus inflows. The elementary process “energy dissipation” is specified by a run-up reduction of a constant value (parameter rl): $nR_0 = R_0 - rl$ if $rl > R_0$ else $nR_0 = 0$.

- Despite experiments carried out on real cases were satisfactory, the above described versions were not suitable for the simulation of debris flows which are characterized by strong soil erosion and entrainment along the landslide path. Hence, the (S_x) family versions were developed (D’AMBROSIO *et alii*, 2002, 2003a; 2003b) and were firstly tested on the 1998-1999 Campanian debris flows event (IOVINE *et alii*, 2003a; D’AMBROSIO *et alii*, 2007).

Version $S_{3\text{-hex}}$ (D’AMBROSIO *et alii*, 2003b), was characterized by the following main features: X is HEX (for obtaining six flow directions that are the maximum number permitted in a regular plane tessellation), $S = S_A \times S_{TH} \times S_O^6 \times S_{KH} \times S_{D'}$. AMD is specified by $q_0 = A_0 + KH_0 + adh$, $q_d = T_{H0} - adh$, $q_i = A_i + TH_i$, $1 \leq i \leq 6$ and $nTH_0 = TH_0 + \sum_{1 \leq i \leq 6} (I_i - O_i)$ is the new thickness. nE_0 is computed similarly, considering the balance of outflows (remaining energy) and inflows (acquired energy). The energy dissipation is the same as O version. The erosion occurs when $E > mt$ (where mt is a threshold parameter); the eroded quantity of the soil cover is $-\Delta D = (E - mt) - er$ if $(E - mt) - er < D$ else $-\Delta D = D$ (where er is the erosion parameter).

It must be pointed out that the parameter er in its present form is an empirical parameter and is not related to any traditional governing equations for erosion (e.g., EGASHIRA 2007). A more rigorous treatment of this parameter is one of the planned future improvements of the model.

Version S_4 (D’AMBROSIO *et alii*, 2006), holds the general setting up of S3-hex, but improves the management of inertial effects by introducing indicators of momentum S_{px} and S_{py} .

Velocity “indicators” v are deduced for cell inflows and remaining debris in the cell, considering their associated kinetic head, by formula $KH = v^2/2g$, and their momentum “indicators” are deduced considering their mass. Two components PX and PY (respectively along axes x and y) are computed by the sum of all the contributions. A “height” alteration, based on PX and PY, in the neighbouring cells was introduced in AMD for S_4 in order to opportunely account for inertial effects along the motion directions.

However, in spite of the relevant improvements described above, the SCIDDICA models were still affected by a relevant limitation: the flow velocity could be only deduced “a posteriori” by averaging in space (i.e. considering clusters of cells and computing the resulting velocity for all cluster flows) or in time (e.g. considering the average velocity of the advancing flow front in a sequence of CA steps) since the flow moves from a cell to another one in a CA step (which corresponds to a constant time). Hence, in the CA context of discrete space/time, “velocity” is constant.

- This limitation has been resolved in the version (SS2) (AVOLIO *et alii*, 2008, 2009; MAZZANTI *et alii*, 2009) by applying the same approach previously developed for the lava flow model SCIARA (AVOLIO *et alii*, 2006b). This approach is based on the introduction of barycentre co-ordinates for debris flows, thus obtaining “explicit” velocity. Furthermore, this version was significantly improved, in order to simulate combined subaerial-subaqueous debris flows, by introducing different parameters and different transition functions for the modelling of both the subaerial and the submerged path at the same time. Effects like loss of energy and loss of material at the air-to-water transition were added instead.

In this version X is HEX, while $S = S_A \times S_{TH} \times S_X \times S_Y \times S_{KH} \times S_{SE} \times S_{XE} \times S_{YE} \times S_{XI} \times S_{YI} \times S_{OE} \times S_{OP}$. AMD and erosion are the same as S3-hex. Regarding co-ordinates X and Y; its

“form” (as the form of outflows) is ideally a “cylinder” centred at the barycentre and tangent to the next edge of the hexagonal cell. Outflows move on such ideal path, whose shift are computing according to the simple kinetic formula which depends whether the flow is subaerial or subaqueous. In fact, the shift formula for subaqueous debris considers also a water resistance parameter, using modified Stokes equations (AVOLIO *et alii*, 2008) with a form factor parameter which is proportional to mass and a parameter $g' < g$, accounting for buoyancy. The motion involves three possibilities: (1) only internal flow (the entire debris remain inside the cell); (2) only external flow (all the debris moves to the adjacent cells); (3) the flow is divided between the central and the adjacent cell (a part of the debris remains inside the cell and a part of it moves towards adjacent cells). The kinetic head variation is computed according to the new position of internal and external flows; furthermore, a contribution

of energy dissipation by turbulence is expressed by $-\Delta KH = tdKH$, where td is the turbulence dissipation parameter. The resulting new mass, barycentre and energy (related to velocity) are computed by the composition of all the inflows from the neighbors and the residual quantities inside the cell. 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 water cell (altitude lower than water level) implies always a loss of matter (water inside debris and components lighter than water) proportional to debris mass, specified by a parameter ml .

SCIDDICA-SS2 was tested on the 1997 subaerial-subaqueous debris flow at Lake Albano (Rome, Italy) and on a recent completely submarine debris-flow, in the nearshore of Bagnara Calabria (Italy).

- A further improvement of SCIDDICA (SS-2blocks) was devised in order to simulate landslides characterized by the presence of large blocks inside the main landslide debris. Blocks are idealised as cylinders; they move 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 classic motion equations (see at AVOLIO *et alii*, 2009 for further details).

- Latest developments of the model regard the management of the interaction between the debris flow and different types of man-made structures (i.e. houses, cables, pipelines, and defenses structures) both in subaerial and in submerged environment

SUSCEPTIBILITY ANALYSIS

Susceptibility analysis of debris flow impact on human settlements and structures is the basic requirement for risk assessment and reduction strategies. Simple susceptibility analyses have been performed by SCIDDICA S3-hex in recent years (Iovine et al. 2002; 2003a; 2003b; 2005; 2007).

Basic information required for such analysis are: (i) detailed topographic data; (ii) map of the erodible soil cover overlying the bedrock; (iii) location of landslide sources; (iv) areal and volumetric size of landslide sources; (v) back analysis simulation of real landslides occurred in the same area necessary for the calibration of model parameters; (vi) validation of the model by the comparison of real and simulated events.

In Fig. 2 an example of a simple susceptibility zonation is shown, where different grey-tones are as-

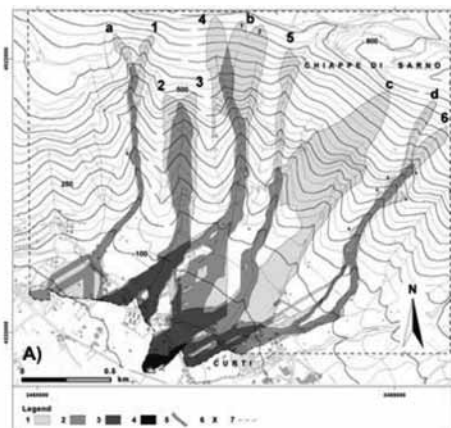


Fig. 2 - Debris-flow susceptibility map of the southern slope of the Pizzo d'Alvano massif: ten soil-slip sources have been considered (case a, b, c, d correspond to the may 1998 debris flows) along the southern slope of Pizzo d'Alvano. Area "potentially" affected by one (1), two (2), three-four (3), and five-six (4) simulated landslides; 5) wall; 6) secondary soil slips; 7) border of the area considered in simulations

signed to zones affected by one/more simulated phenomena. Specifically, areas affected by only one of the simulated landslides are considered less susceptible (light gray) than zones affected by more landslides (dark gray). More sophisticated and powerful approaches for susceptibility analysis have been developed by our research group and tested on lava flows (CRISCI *et alii*, 2010). A similar approach could be applied (with some modifications) to the susceptibility analysis of debris flows.

DEBRIS FLOW SIMULATION BY SCIDDICA

Simulations by SCIDDICA of four debris flow events occurred in Italy in the recent years are presented below. Specifically, simulations of two completely subaerial debris flows (Chiappe di Sarno-Curti, 1998 and San Martino Valle Caudina, 1999), one submarine debris flow (Bagnara Calabria, 2008) and one mixed subaerial-submerged debris flow (Lake Albano, 1997) are shown. A short description of simulation results are also presented together with a quantitative evaluation of simulations according to a fitness function based on the areal comparison of real and simulated event (D'Ambrosio & Spataro, 2007). Specifically, the considered evaluation function is

$$ev = \sqrt{((R \cap S) / (R \cup S))}$$



Fig. 3 - The 1998 Curti DF: comparison between the real case and the best simulation. (1) area affected by real landslide, (2) simulated landslide, (3) both cases; and (4) border of the area considered for comparison

where R is the set of cells involved in the real event and S the set of cells involved in the simulated event. A value between 0 (total failure) and 1 (perfect simulation) is obtained, with values greater than 0.7 considered as satisfactory for landslide simulations

CHIAPPE DI SARNO-CURTI

On May 5–6 1998, about 150 debris flows were triggered by exceptional rainfalls in Campania (Southern Italy), mostly on the slopes of Pizzo d'Alvano massif. Hundreds of small debris slides originated in the volcanoclastic mantle overlying carbonate bedrock and propagated downslope as an extremely rapid, highly erosive debris flow, dramatically increasing their volume (ZANCHETTA *et alii*, 2004). One of these events took place in the Chiappe di Sarno slope. The size of the detachment area was approximately 100 m², and the volume of the involved material was less than 100 m³. The sliding mass rapidly transformed into a fast-flowing mixture of mud, debris, and water, running down the slope along a smooth pre-existing channel, for about 375 m, and eroding the available detrital cover. The debris flowed for a distance of about 325 m, triggering some minor debris slides on both flanks of the channel. After that, influenced by the pre-existing morphology, it made a left turn, enlarged, and subdivided into two distinct flows.

Simulation of this event was performed by SCIDDICA **S3-hex**. A graphic comparison between the map of the best simulation, and the real case is shown in

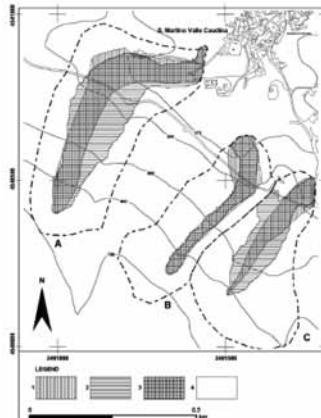


Fig. 4 - The 1999 San Martino Valle Caudina DF: comparison between the real case and the best simulation. (1) area affected by real landslide, (2) simulated landslide, (3) both cases; and (4) border of the area considered for comparison.

Fig. 3. As one can see, the overall area affected by the DF and depth of regolith erosion along the path are in good accordance with surveyed evidences; the branching of the flow at the base of the slope is fairly well simulated. The obtained ev fitness value was 0.76-0.78 (D'AMBROSIO *et alii*, 2003a-b)

SAN MARTINO VALLE CAUDINA

On December 15th–16th, 1999, heavy rainfalls severely stroke the Campania region (Italy), triggering numerous debris flows on the slopes of the Monti di Avella massif (VITTORI *et alii*, 2000). Several soil slips originated on the slopes of the Vallone Castello (Cervinara) and Mt. Pizzone (San Martino V.C.), within the weathered volcanoclastic mantle. These landslides turned into fast flowing mixtures of matrix and large blocks, downslope eroding the soil cover and increasing their original volume. At the base of the slopes, debris flows impacted on the cited urban areas, causing one casualty and severe destruction. Simulation of this event was performed by SCIDDICA S4. A graphic comparison among real landslides and “best” simulations is shown in Fig.4 (IOVINE *et alii*, 2003b). The achieved ev fitness values were 0.77, 0.86 and 0.64 for the case A, B and C respectively (Fig.4). These results demonstrate the efficacy of the SCIDDICA models to simulate also cases of open channel debris flows (mudflows).

ALBANO LAKE

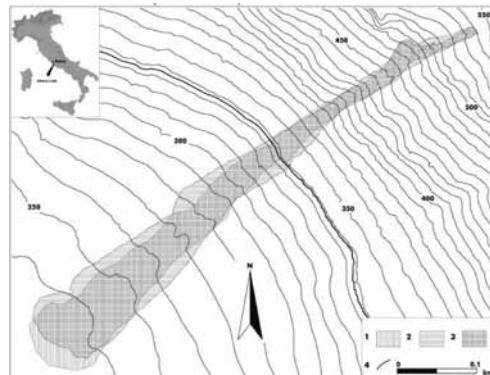


Fig 5 - The 1997 Albano lake subaerial-subaqueous debris flow as simulated by the SCIDDICA SS2 model. Key: (1) real event, (2) simulated event, (3) intersection between real and simulated event, (4) water level

The SCIDDICA SS2 model was validated against the 1997 Albano lake (Rome, Italy) event (Figure 5) which is a rare case of combined subaerial-subaqueous debris-flow. This landslide occurred in the eastern slope of the Albano lake on the 7th of November 1997 after an intense rainfall event (128 mm in 24 hours), and it began as a soil slide, mobilizing about 300 m³ of eluvial material. The mobilized mass was channelled within a steeply dipping impluvium (about 40°) and thus evolved as a debris flow which entrained a large amount of debris material along the bottom of the channel and reached an estimated volume of some thousands of m³ 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. Simulation results are quite satisfactory since the achieved fitness function ev value was 0.85 (AVOLIO *et alii*, 2008). Furthermore, results show a good agreement also in terms of erosion and deposits on both subaerial and subaqueous parts and reasonable values of the landslide velocity (up to 15 m/s).

BAGNARA CALABRA

A completely submarine landslide was detected in the nearshore of Bagnara Calabria (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 m and 20 m b.s.l., about 100 m far from the coastline. Initial landslide volume

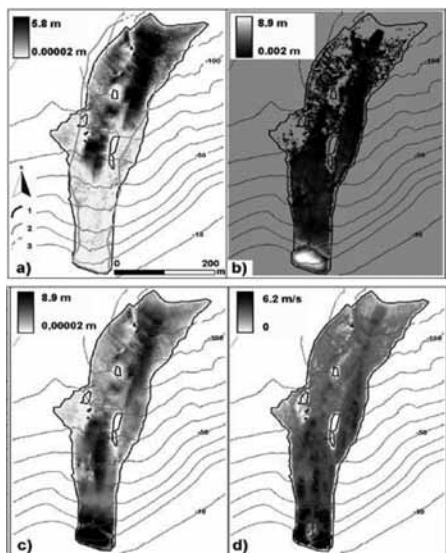


Fig 6 - simulation of Bagnara Calabria subaqueous landslide: a) deposit thickness, b) erosion, c) maximum occurred debris thickness; d) maximum velocity; contour lines are referred to: 1 perimeter of the simulated event; 2 perimeter of real event; 3 probable real event perimeter in missing data area

was also estimated at about 16.000 m³ with a maximum thickness of 9 m. 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 fitness value of 0.85 was achieved for this landslide (AVOLIO *et alii*, 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. The detachment area was completely emptied after about one minute 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 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°). Fig. 6 shows an example of possible output layers than can be obtained by SCIDDICA SS2 and specifically: final deposit thickness, erosion thickness and maximum velocity.

COMPARISON OF SCIDDICA SIMULA-

Debris flow features	Models versions				
	T	O	S ₂	S ₄	SS ₂
Moving Landslide Mass					
Deposition along the flow path					
Erosion and Entrainment along the path					
Secondary Sources Activation					
Processes of Run-up					
Explicit Energy					
Energy Loss					
Explicit Velocity					
Momentum					
Branching or Merging of the Flowing Material					
Loss of Matter and Energy at the Air-Water Interface					

Tab.2 - features of the SCIDDICA versions

TION WITH OTHER MODELS

Simulations carried out by SCIDDICA have been recently compared with simulations by other debris flow models. In particular, the 1997 Lake Albano debris flow has been simulated by SCIDDICA SS2 as well as by *DAN-W* (HUNGR, 1995) and *DAN3D* (MCDUGALL & HUNGR, 2004). Results achieved by *DAN3D* and SCIDDICA were surprisingly similar in terms of areal debris distribution, velocity and time of propagation (MAZZANTI *et alii*, 2009) while results obtained by *DAN-W* show a significant discrepancy. This is once more a confirmation of the limitations affecting 2D models, particularly for the simulation of channeled events like debris flows.

CONCLUSION REMARKS AND OUTLOOKS

A state of the art description of Cellular Automata models for the simulation of debris flows has been presented together with some examples of application to real events occurred in Italy in recent years. Thanks to the significant improvements made in the latest years, and briefly summarized in this paper in a chronological way (Tab.2), Cellular Automata models can now be considered as a powerful and reliable tool for the simulation of debris flows and hyper-concentrated flows. In particular, the introduction of explicit velocity (in the SCIDDICA version SS2) has brought these models to the same level of the most accepted codes as *DAN3D*

Main criticisms moved to such models argue that they are not fully physically based. However, with the introduction of explicit velocity, the management of momentum (even if yet in a rough way) and the introduction of turbulence forces, which can be found in the latest versions of SCIDDICA, the main requirements of the “equivalent fluid” approach (HUNGR, 1995) are satisfied.

Rather, a general critic could be moved to the efficacy of the equivalent fluid approach which assumes a complex mixtures of water and heterogeneous debris (which often changes its features during the propagation) to behave as an equivalent and homogeneous fluid (usually integrated in depth) controlled by only 2 or 3 parameters. It is evident that this is a very strong approximation; however, at this time, models based on the equivalent fluid approach are probably the only ones able to give reasonable results (in a reasonable time of computation).

As a matter of fact, the most advanced models based on the equivalent fluid approach like SCIDDICA SS (i.e. McDougall & Hungr, 2004; Pirulli et al., 2010) are able to simulate the main characteristic of debris flows, such as:

- (i) propagation of debris in channeled slopes over a 3D topography;
- (ii) erosion and entrainment of material along the path;
- (iii) interaction with structures;
- (iv) immersion in water (in the case of costal DF).

Nevertheless, it must be pointed out that users and researchers which intend to use such an approach must be completely conscious of these limitations.

Furthermore, these models have been tested by simulating several real events, and are now able to give good results also in terms of forecasting analyses. In particular, forecasting instruments for DF impact are a fundamental tool for the society in order to produce hazards maps which must become the basic data for the landscape management. The first step in this direction has been already carried out with the SCIDDICA models by using a simple approach for susceptibility analysis. However, more sophisticated

and reliable approaches are under development (i.e. Crisci *et alii*, 2010; Cepeda *et alii*, 2010).

On the other hand, it must be pointed out that some improvements of the SCIDDICA model are still possible. First of all, a new solution for the management of the momentum is needed, as the importance of non isotropic internal earth pressure (Savage & Hutter, 1989) for landslide simulation has been demonstrated (Pirulli *et alii*, 2007). This is one of the main tasks for the next future, even if the approximation of hydrostatic internal earth pressures does not lead to significant mistakes in the case of debris flows with a high percentage of water (Cepeda, 2007; Mazzanti *et alii*, 2009).

A most advanced computation of erosion process is also under development with specific reference to the erosion parameters.

A further improvement required to the SCIDDICA model is the introduction of explicitly interactions between solid and fluid-phases on the debris as the relevance of inner fluid pressures in the propagation of a debris flow has been demonstrated (Iverson, 1997).

A new objective is an efficient management of the interaction of debris flow with man made structures. First preliminary results have been achieved for testing the resistance of submarine cables, even if significant improvements are still necessary.

However, in spite of the aforementioned approximations, the last versions of the SCIDDICA are quite stable, well-performing and suitable for the simulation of different types of debris flows in different environments. In other words, SCIDDICA can be considered a valid and efficient tool for the susceptibility analysis of debris flow run-out at a local or global scale.

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