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SCIDDICA-SS_3: a new version of cellular automata model for simulating fast moving landslides

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Abstract Cellular Automata (*CA*) are discrete and parallel computational models useful for simulating dynamic systems that evolve on the basis on local interactions. Some natural events, such as some types of landslides, fall into this type of phenomena and lend themselves well to be simulated with this approach. This paper describes the latest version of the SCIDDICA CA family models, specifically developed to simulate debris-flows type landslides. The latest model of the family, named SCIDDICA-SS_3, inherits all the features of its predecessor, SCIDDICA-SS_2, with the addition of a particular strategy to manage momentum. The introduction of the latter permits a better approximation of inertial effects that characterize some rapid debris flows. First simulations attempts of real landslides with SCIDDICA-SS_3 have produced quite satisfactory results, comparable with the previous model.

Keywords Cellular automata · Modelling · Debris flows · SCIDDICA

1 Introduction

Many natural phenomena, like some complex fluid-dynamical phenomena, are difficult to be modelled through standard approaches, such as differential equations [1]. As a consequence, innovative numerical methods emerged from alternative computational paradigms such as Cellular Automata (*CA*), Neuronal Nets, Genetic Algorithms, etc. (cf. [2–4]).

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It is worth to note that some natural events are difficult to be simulated by valid existing models at a “microscopic” or “mesoscopic” level since they generally evolve on very large areas, thus needing a “macroscopic” level of description. In this case, Macroscopic Cellular Automata (*MCA*) [5] can represent a valid choice for modelling and simulating these complex dynamical systems like fluid-dynamical natural phenomena. *MCA* are an extension of classical *CA*, and were developed in order to model many natural macroscopic events that seem difficult to be modelled in other *CA* frames, e.g. the Lattice-Boltzmann method ([6, 7]), just because they take place on a large space scale. Debris flows, for example, fall in the category of surface flows that evolve on large scales and are natural candidates to be modelled through two-dimensional *MCA*.

In the last years, *CA* proved to be a valid alternative to differential equations in simulating some complex natural phenomena ([5, 8]) evolving by local interactions. Some researchers, for instance, proposed *CA* models for flow-type landslides: Segre and Deangeli [9] presented a three-dimensional numeric model, based on *CA*, for debris flows, using difference equations. The model was validated on the M. XiKou landslide, capturing its main characteristics. Clerici and Perego [10] simulated the Corniglio landslide using a simple *CA* model in order to capture the blockage mechanisms for that type of landslide. Salles et al. [11] developed recently a first interesting *CA* model for subaqueous flows, in order to simulate density currents.

Di Gregorio et al. [12] developed a simple two-dimensional *MCA* model (first release of SCIDDICA) for simulating landslides of debris-flows type and initially validated it by simulating the Mt Ontake landslide and later applied for simulating the Tessina slow-moving earth flow [13]. Many extensions of SCIDDICA were afterwards developed by Di Gregorio and co-workers [14] in order to improve the model and/or capture the characteristics of different or more complex landslides [12, 13]. Moreover, the same kind of *MCA* are also adopted for simulating other phenomena, such as different types of lava flows [15], pyroclastic flows [16], avalanches [17] and, in their latest application, for combined subaerial-subaqueous landslides [18].

In the present paper, the latest SCIDDICA-SS_3 hexagonal release of the model is described. SCIDDICA is a family of deterministic *MCA* models [19] for simulating the behaviour of landslides that can be typologically defined as “flows” [20]. This assertion allows us to exploit, on the one hand, the fact that *MCA* of the SCIDDICA family are based on the equivalent fluid principle, formalized by Hungr [21], and, on the other, permits to consider an intrinsic property of *MCA*: they are considered in terms of a-centric system, i.e. systems whose evolution can be described by considering mainly local interactions among their constituent “elementary” parts [22], a typical characteristic of flows.

This latest version (SCIDDICA-SS_3) derives from the need to improve the previous model, SCIDDICA-SS_2 [18], in order to better manage inertial effects. In SCIDDICA-SS_3, by adopting an empirical strategy, the inertial character of the flowing mass is translated into *MCA* terms by means of local rules. In general, all SS_x releases of the SCIDDICA family are an extension to combined subaerial-subaqueous flow-type landslides, with a new flows characterization by their mass centre position and velocity [18]. These characteristics have allowed for a more appropriate characterization of momentum, allowing even for the description of its components along the direction of motion.

While still undergoing a preliminary calibration phase, first simulation attempts by SCIDDICA-SS$_3$ were performed by taking into account a real case of debris flows, namely the subaerial-subaqueous event which took place near the lake of Albano (central Italy) in 1997. In the following sections, the model description and produced results are presented.

2 MCA for surface flows

For *MCA* modelling purposes [5], landslides can be viewed as a dynamical system that evolves within a limited portion of the space, tessellated into regular cells (e.g. square, hexagonal). A *state* is defined for each cell that describes the physical characteristics of the corresponding portion of space; in particular, in the *MCA* framework the *states* of the cell are decomposed into *substates*, or rather the *state* of each cell can be expressed by the Cartesian product of all the considered *substates*, where each *substate* represents a particular feature of the phenomenon to be modelled (e.g., the altitude, depth of soil cover, thickness of landslide debris, landslide energy, etc.). *Elementary processes* constitute the *transition function* (τ) of the model: this is composed of a set of rules which describe *local processes* constituting the overall phenomenon. In addition, some *parameters* (e.g. the temporal *MCA* clock, cell dimension, etc.) are generally considered, which allow to "tune" the model for reproducing different dynamical behaviours of the phenomenon of interest, by taking into consideration their physical/empirical meaning. At the beginning of the simulation, cell *states* are initialized by means of input values (e.g., through matrices). Model *parameters* have also to be assigned in this phase. By simultaneously applying the *transition function*, τ, to all cells and at discrete steps, *states* are changed and the evolution of the phenomenon can be simulated.

Natural macroscopic phenomena, which evolve by generating flows of material and involving surface-flows can be modelled through two-dimensional *MCA*, because the third dimension (i.e., the height) can be managed as a property of the cell (i.e., a *substate*). Thus, it is possible to consider characteristics of the cell (i.e., *substates*), typically expressed in terms of volumes (e.g., debris volume), here in terms of thickness. This simple assumption permits to adopt an efficacious strategy by means of the *Minimization Algorithm of the Differences* [5] (*MA* in the rest of the text), based on the hydrostatic equilibrium principle, in order to compute outflows of material (e.g., debris in the case of landslides) from a central cell to the neighbouring ones, and by adapting the *MA* algorithm depending on the particular simulated phenomenon [23]. The *MA* gave rise to several models for different macroscopic phenomena: lava flows [23], debris/mud flows [5] and rain soil erosion [24] are among the most notable.

3 The SCIDDICA-SS$_3$ MCA model

As already mentioned, SCIDDICA is a family of deterministic *MCA* models, with hexagonal cells, specifically developed for simulating flow-type landslides. The

SCIDDICA family includes many versions developed in previous years, from the first release [13], named T, to the latest SCIDDICA-SS$_2$ [18]. This development is also due to a continuous refinement of the adopted approach, which has furthermore given rise to a more physical modelling framework with the development of the SCIDDICA-SS$_3$ model. The model's *transition function* latest improvements include a better management procedure for inertial effects which characterize rapid debris flows. In fact, a first attempt of the introduction of momentum was made in an earlier version, named SCIDDICA-S$_4$ [25], but the lack of explication of the mass centre did not allow to exploit the full potentiality of the model and was soon abandoned. As a matter of fact, the introduction of the mass centre (or barycentre) in the SS$_\text{x}$ models has allowed a better approximation of the phenomenon from the physical point of view, so to allow to compare the SCIDDICA-SS$_\text{x}$ model with other well-known debris-flows models [26]. For instance, a test has regarded the comparison of simulation results of the 1997 Lake Albano (Lazio Region, Italy) debris flow carried out by SCIDDICA-SS$_2$ and the well-known DAN3D [27] software. Results achieved by DAN3D and SCIDDICA-SS$_2$ were surprisingly similar in terms of areal debris distribution, velocity and propagation time [26].

The SS$_x$ releases have been implemented both for the need to simulate combined subaerial-subaqueous landslides and to make velocity explicit, a methodological approach firstly applied to lava flows ([28, 29]). The precedent release of the SS$_x$ SCIDDICA family overcomes a typical restriction of many *CA* models, including Lattice-Boltzmann [6] ones: a fluid amount moves from a cell to another one in a *CA* step, which corresponds usually to a constant time. This implies a constant local "velocity" in the *CA* context of discrete space/time. Nevertheless, velocities can be deduced by analysing the global behaviour of the system in time and space. In such models, the flow velocity emerges by averaging on the cell space (i.e., considering clusters of cells) or by averaging on time (e.g., considering the average velocity of the advancing flow front in a sequence of *CA* steps).

Constant velocity could be a limit for modelling finely macroscopic phenomena, because it is sometimes difficult to introduce physical considerations in the modelling at a local level. Furthermore, the time corresponding to a step of the *CA* is often deduced "a posteriori" by the simulation results and parameters of the transition function must be again verified when the size of the cell is changed. A solution was proposed in SCIDDICA-SS$_\text{x}$ models [18]: moving flows toward the neighbouring cells are individuated by the substates mass, velocity and barycentre co-ordinates. The resulting new mass, barycentre and velocity are computed by composition of all the inflows from the neighbours and the residual quantities inside the cell.

Moreover, in the last version (SCIDDICA-SS$_3$), a new empirical strategy has been introduced for the determination of outflows from a cell toward its adjacent cells (the other of the neighbouring cells). Such a strategy, intuitively discussed later on before its formalization in Sect. 3.1, has permitted to improve significantly the precision in the complicated computation of momentum for the flowing masses in the *MCA* context, where a macroscopic view was adopted.

The starting point is the *MA*, where outflows from a cell are computed in order to obtain hydrostatic equilibrium in the neighbouring cells. In a cell, inflows and mass inside are composed as quantity, mass centre, kinetic energy and momentum.

Momentum introduces an alteration of hydrostatic equilibrium, which is translated in terms of the *MA* by modifying fictitiously altitudes of adjacent cells: altitude is opportunely lowered/raised according to the module and direction of momentum.

Then, the computation proceeds by two stages:

(a) outflows toward the neighbouring cells are computed in the condition of different altitude alterations: this represents the situation of flows that just can overcome obstacles, neglecting other interactions;
(b) the part of mass that cannot overcome obstacles is considered to interact strongly with such obstacles, in a complicated play of hitting and bouncing, where momentum disappears and part of kinetic energy is lost. Because of lack of directionality and by considering the remaining kinetic energy, the *MA* is again applied with a new altitude variation (proportional to the residual kinetic energy of the cell that distributes a flow toward neighbouring cells). This permits to compute outflows toward cells penalized by the direction of momentum in the previous stage.

3.1 Formal definition of SCIDDICA-SS$_3$

As anticipated, SCIDDICA-SS$_3$ is a bi-dimensional model, based on hexagonal cells (even if simulations are effectively three-dimensional, because the third dimension is included in the specification of the cell state), that is able to simulate debris flow like landslides that evolve in air and/or under water.

The release SS$_3$ of SCIDDICA is formally defined by the quintuple:

$$\text{SCIDDICA-SS}_3 = \langle R, X, Q, P, \tau \rangle$$

where:

- $R = \{(x, y) \in Z^2 | -l_x \le x \le l_x, -l_y \le y \le l_y\}$ identifies the hexagonal cellular space where the phenomenon evolves; Z is the set of the integer numbers;
- $X = \{(0,0), (1,0), (0,1), (0,-1), (-1,0), (-1,1), (1,-1)\}$ is the geometrical pattern of the neighbourhood of the cell, Fig. 1, given by the "central" cell and its six adjacent cells;
- $Q = Q_{X1} \times Q_{X2} \times \cdots \times Q_{Xn}$ is the finite set of states given by the Cartesian product of the sets of the considered *substates* (Table 1). The value of the *substate* x in the cell is expressed by $q_x \in Q_x$. In the following, q_x indicates the values of a substate Q_x. When substates need the specification of the neighbouring cell, the neighbour index is indicated between brackets;
- P is the set of the global parameters [18] (Table 2) which account for the general frame of the model and the physical characteristics of the phenomenon. In Table 2, the "$*$" symbol at the end of the parameter name is considered when the formula is valid both in water and air.
- $\tau : Q^7 \to Q$ is the deterministic transition function for the cells in R.

  At the beginning of the simulation (for $t = 0$), the states of the cells in R must be specified, defining the initial configuration of the *MCA*. Initial values of the substates (Table 1) are initialized as follows:

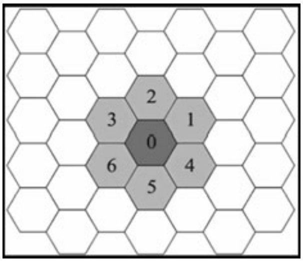

Fig. 1 The neighbourhood adopted in SCIDDICA-SS$_3$. Key: the central cell is individuated by the index “0”; indexes 1–6 identify the cells of the neighbourhood

Table 1 SCIDDICA-SS$_3$: list of considered substates

Substate	Meaning
Q_a	Altitude (in metres)
Q_{th}	Thickness of landslide debris (in metres)
Q_d	Maximum depth of detrital cover that can be transformed by erosion in landslide debris, depending on the type of detrital cover (in metres)
$Q_o(Q_i)$	Debris outflow (inflow) (in metres)
Q_E	Total energy of landslide debris (in joule)
Q_{px}, Q_{py}	Represent indicators of the momentum of the landslide debris, along the outflow velocity directions (in kg m/s)
Q_x, Q_y	Coordinates of the debris barycentre with reference to the cell centre (in metres)
Q_{kh}	Debris kinetic head (in metres)
$Q_{oe}(Q_{oi})$	Part of debris flow, the so-called “external flow” (“internal flow”), normalized to a thickness, that penetrates the adjacent cell from central cell (that remains inside the central cell) (in metres)
$Q_{XE}, Q_{YE}(Q_{XI}, Q_{YI})$	Coordinates of the external flow barycentre (internal flow barycentre) with reference to the adjacent cell centre (in metres)

Table 2 SCIDDICA-SS$_3$: list of considered parameters

Parameter	Meaning
p_c	Side of the cell (in metres)
p_t	Temporal correspondence of a step of SCIDDICA (in seconds)
p^*_{adh}	Water/air adherence value (i.e. unmovable amount of landslide debris) (in metres)
p_{f*}	Water/air height threshold (related to friction angle) for debris outflows. It is expressed as the minimum difference of height between two cells for the debris distribution to be allowed (dimensionless)
p_{mt^*}	Water/air activation threshold of the mobilization (in metres)
p_{er^*}	Water/air parameter of progressive erosion of the soil cove (dimensionless)
p^*_{td}, p^*_{ed}	Water/air parameters for energy dissipation by turbulence and by erosion respectively (dimensionless)
p_{ml}	Matter loss in percent when the debris enters into water (dimensionless)
p_{wr}	Water resistance parameter (dimensionless)

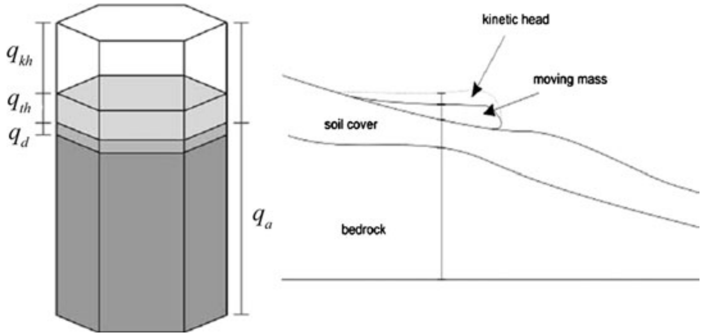

Fig. 2 *Left*: relationship in a hexagonal cell between the values q_a, q_d and q_{th} of the substates Q_a, Q_d and Q_{th}, respectively, and of the kinetic head q_{kh}. *Right*: an ideal vertical section of a debris flow along a slope is also given

- Q_a is set to the cell altitude a.s.l. (bedrock elevation plus depth of soil cover); in the landslide source, the thickness of the landslide debris is subtracted from the morphology;
- Q_{th} is zero everywhere—except for the source area, where the landslide debris thickness is specified;
- Q_E is zero everywhere—except for the source area, where it is equal to the potential energy of the landslide (with reference to the cell altitude);
- Q_d is the depth of the soil cover, which can be eroded by the landslide along the path;
- All remaining substates are set to 0 everywhere.

The transition function τ is applied, step by step, to all the cells in R, and the *MCA* configuration changes obtaining the evolution of the simulation.

Basic assumptions An important requirement regards the energy definition which is used in the last releases of SCIDDICA. Let us first consider a "column" of mass m (with constant density ρ), with base A and thickness $h = q_{th}$ at altitude $z = q_a$ (with respect to the plane $z = 0$) (Fig. 2), which moves at velocity v. If E_u and E_k represent the potential and the kinetic energy, respectively, the total energy of the column, E, is given by the following expression:

$$E = E_u + E_k = \rho g A \int_z^{z+h} z\,dz + \frac{1}{2}\rho A h v^2$$

where g is gravity acceleration. In hydrodynamics [30], the kinetic head, h_k, is defined as $h_k = v^2/2g$. Thus:

$$E = \rho g A h\left(\frac{1}{2}h + z + h_k\right) \tag{1}$$

while

$$E_k = \rho g A h h_k \quad \text{and thus } h_k = \frac{E_k}{\rho g A h} \tag{2}$$

These “singular” considerations are useful, as SCIDDICA models generally handle “quantities” in terms of heights (e.g. debris volume in debris thickness, debris energy in kinetic height).

3.2 Main characteristic of transition function τ of SCIDDICA-SS_3

Since SCIDDICA-SS_3 inherits all the features of the previous model’s transition function, we briefly describe here the elementary processes of SS_3 that have undergone slight changes (or none) with respect to SS_2, indicated in the following by (τ_{SS_2}, τ_{SS_3}), while new SS_3 elementary processes, indicated in the following by (τ_{SS_3}) (e.g., computation of debris outflows) are herein described in detail. For more specifications on the elementary processes of SS_2, see [18].

Mobilization effects (τ_{SS_2}, τ_{SS_3}): An empirical strategy has been developed to better simulate the partial erosion of the regolith along the path of the landslide. In practice, when the kinetic energy overcomes an opportune threshold (p_{mt}), then a mobilization of the detrital cover occurs proportionally to the quantity overcoming the threshold. All heights q_a, q_d, and q_{th} and relative energies q_{kh} and q_E are updated as soil is eroded. This elementary process has not been modified with the addition of momentum.

Computation of debris outflows (τ_{SS_3}*)* In all SCIDDICA versions, outflows from the central cell toward the neighbouring ones are computed by applying the *MA* ([5, 28]). The algorithm is based on the following assumptions:

– In the central cell, an unmovable amount, $u(0)$, and another one which can be distributed to the neighbours, m, are in general considered; the latter is computed as

$$m = \sum_{i=0}^{6} q_o(i)$$

where $q_o(i)$ is the flow toward the cell i and $q_o(0)$ is the part of m which remains in the central cell

– The content of the adjacent cells, $u(i)$ $(i = 1, 2, \ldots, 6)$, is considered unmovable.

Aiming at emphasizing inertial effects of rapid debris flows, in the release SS_3, some directions are privileged according to the momentum of the debris inside the cell. In this regard we consider (d_x, d_y) the directional components of the velocity of outgoing flows from one cell and applied at the corresponding centre of mass (Fig. 3a). Along the directions (d_x, d_y) it is possible to compute the two indicators (q_{px}, q_{py}) of the momentum given in module as

$$p = \rho A q_{th} \sqrt{2 g q_{hk}}$$

where ρ is the density of the material of the landslide, A the area of the cell, q_{th} the thickness of debris in a cell, g the gravity acceleration and q_{kh} is the kinetic head of the landslide. By means of simple conventional geometric processes (cf. Fig. 3a), the segments $\overline{P_{i(n)} P_{i(n+1)}}$ are identified, where i refers to the neighbouring cell i and,

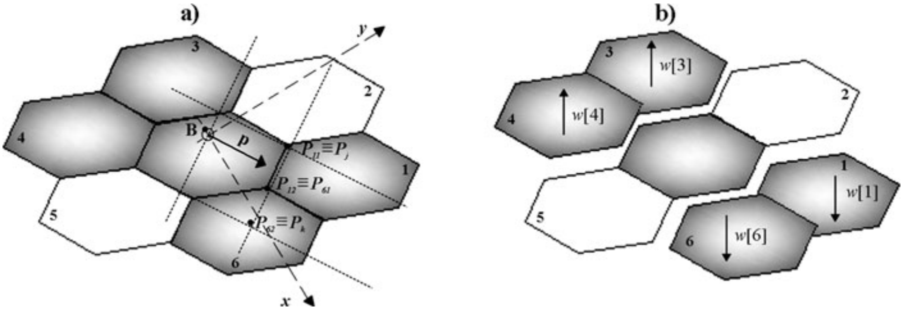

Fig. 3 An example of cell elevation alteration for emphasizing inertial effects. Shaded colouring indicates cells (numbered 1 through 6) affected by the procedure. (**a**) B is the barycentre of the mass inside a generic central cell with momentum module p. Segments $|\overline{P_{i(n)} P_{i(n+1)}}|$ are determined by $|\overline{P_{11} P_{12}}|$ and $|\overline{P_{61} P_{62}}|$ for cells 1 and 6, respectively; (**b**) In the first phase of distribution step, the elevation of cells 1 and 6 are decreased by quantities $w[1]$ and $w[2]$, respectively, while elevations of cells 3 and 4 are increased by the same quantities

proportionally to these segments, the amount of motion is "distributed", in module, to the neighbouring cells according to the formula

$$p_i = \frac{p \times |\overline{P_{i(n)} P_{i(n+1)}}|}{|\overline{P_j P_k}|}$$

where p_i indicates the part of the momentum which is "transferred" into the cell i, $|\overline{P_{i(n)} P_{i(n+1)}}|$ the length of the segment corresponding to the cell i and, at last, $|\overline{P_j P_k}|$ is the total length of the segment that goes from P_j to P_k (Fig. 3a). The cells toward which $p_i \neq 0$ are considered as *privileged* ones, as mentioned previously. Within the context of the hexagonal cellular space, along these latter the effect of momentum has to be stronger in order to account for the inertial properties of the debris flow. By definition, if for instance $p_i > p_j$, the direction toward cell i is the most privileged.

With the aim of privileging the directions defined by the various p_i, in SCIDDICA-SS$_3$ the heights (i.e., cell altitude plus landslide thickness) of the neighbouring cells are increased by an amount $w(i)$, $(i = 1, 2, \ldots, 6)$, computed as follows (cf. Fig. 3b):

- $w(i) = -\alpha p_i$, for neighbouring cells i which have $p_i \neq 0$;
- $w(i) = \alpha p_i$, for cells opposite to cells with $p_i \neq 0$;
- $w(i) = 0$ for cells not involved in the motion;

where α is a proportionality coefficient of kinetic energy.

In such a way, the *MA* will give privilege, in the distribution of the landslide debris, to those cells whose heights are most decremented.

According to the previous considerations, an empirical double-phase strategy was developed in SS$_3$ to account for the inertial effects of rapid debris flows. In the first phase, inertial outflows ($q'_0(i)$) are computed first, introducing a sort of "weakening" of privileged senses. The MA is applied in the following form:

$$m = q_{th}(0) - p_{adh}$$

$$u(0) = q_a(0) + p_{adh} + q_{kh}$$

$$u(i) = q_a(i) + q_{th}(i) + w(i)$$

where p_{adh} represents the water/air parameter of the adherence value (i.e., unmovable amount of debris in a cell).

The remaining debris thickness in the central cell is accordingly reduced to the value

$$new\_q_{th}(0) = q_{th}(0) - \sum_{i=1}^{6} q'_0(i)$$

while, for the receiving cell i,

$$new\_q_{th}(i) = q_{th}(i) + q'_0(i)$$

This phase obviously involves also the update of the energy new_q_E and new_q_{kh}, for both the central and neighbouring cells i receiving a flow.

In the second phase, by considering the eventual residual debris, new_q_{th} (i.e., the debris not distributed during the first phase) and kinetic energy, $new\_q'_{kh}$ (i.e., the kinetic energy decreased by the only outflows contribution), not-inertial outflows ($q''_0(i)$) in the cell are computed, assuming the inertial effect to be negligible. The *MA* is now applied in the following form:

$$m = \left[q_{th}(0) - \sum_{i=1}^{6} q'_0(i) \right] - p_{adh}$$

$$u(0) = q_a(0) + p_{adh} + new\_q'_{kh}$$

$$u(i) = q_a(i) + \left(q_{th}(i) + q'_0(i) \right)$$

At the end of the two phases, the total outflows $q_0(i)$ for each cell i of the neighbourhood can be determined as follows:

$$new\_qth = qth - \sum_{i=1}^{6} q'_0(i) - \sum_{i=1}^{6} q''_0(i)$$

while the final debris in the cell 0 is

$$q_0(i) = q'_0(i) + q''_0(i)$$

increased by the sum of the incoming flows, in the central cell 0, of the two kinds of flows determined in the previous two phases.

In order to better understand the functioning of this mechanism, Fig. 4 illustrates a simple example of inertial displacement of a mass, which moves with velocity v (without any frictional loss) along a flat mono-dimensional path. The phenomenon is reproduced by considering a "fictitious" slope, i.e. by adding the amounts $w(1)$ and $w(2)$ to the altitudes of the down- and up-flow cells, respectively. In this way, the *MA* (which does not directly consider velocities) perceives a situation of hydrostatic no-equilibrium that is resolved by moving the whole mass to the adjacent cell,

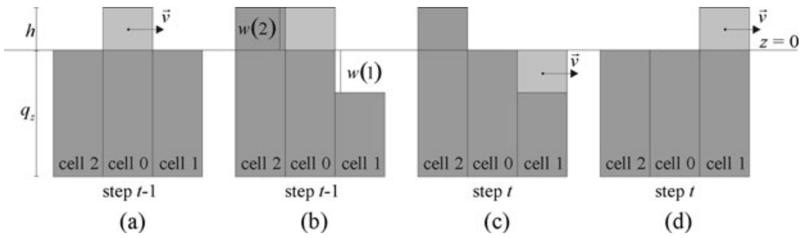

Fig. 4 Example of "inertial" displacement of a debris mass, in case of no dissipative effects. Key: (**a**) At step $t-1$, a mass having thickness h moves along a flat mono-dimensional path with velocity v (such that, at step t, it completely moves to the adjacent cell on the right); (**b**) the same situation can be modelled by considering a fictitious slope, by utilizing the amounts $w(1)$ and $w(2)$. (**c**) By applying the *MA* to the fictitious situation, all the mass moves to the adjacent cell, with resulting velocity v. (**d**) Final situation, in the real slope, at step t. Note that in this case there is only the first stage

thus simulating an inertial displacement. Note that, if such "fictitious" slope were not considered, the *MA* would retain (as before) a part of mass in the central cell, and distribute the remaining part toward the up-slope cell and thus not allowing for the simulation of an inertial displacement.

Shift of the outflows (τ_{SS_2}, τ_{SS_3}) The shift of the outflows is computed for both loops of the same computational step, according to a simple kinetic formula which depends on whether the flow is subaerial or subaqueous (as for SS_2) ([18, 28, 29]). In particular, the shift formula for subaqueous debris considers also the water resistance, using modified Stokes equations with a form factor (p_{wr}) that is proportional to mass.

The substantial difference with SCIDDICA-SS_2 is the calculation of the displacement in the first loop; in fact, at this stage the shift is calculated considering a variation of the height given by the previously described values of $w(i)$.

The movement of flows affects the determination of the computation of the new coordinates of the barycentre, which is calculated as the weighted average of q_x and q_y, considering the remaining debris in the central cell, the internal flows and the inflows, at the end of the two loop phases.

Turbulence effect (τ_{SS_2}, τ_{SS_3}) A total energy reduction, besides the computation of the new total energy amount (new_q_E) in a cell, is considered by loss of flows, while an increase is given by inflows; moreover, the new value of the kinetic head (new_q_{kh}) is deduced from the computed kinetic energy, and energy dissipation (p_{td}, p_{ed}) computed over the kinetic head was considered as a turbulence effect.

Obviously, updates of the total and kinetic energy are carried out at the end of the two phases of a step, that is, after the double distribution of the debris.

Air–water interface (τ_{SS_2}, τ_{SS_3}) Air–water interface regards debris flow crossing from air to water (vice versa is unrealistic). An external flow from an air cell (having altitude higher than water level) to a water cell (having altitude lower than water level) implies always a loss of matter (p_{ml}) proportional to debris mass, specified by an opportune parameter, implying a correspondent loss of kinetic energy, determined by kinetic head decrease. Even this elementary process has not undergone changes with the addition of momentum in the model.

4 SCIDDICA-SS_3 applications

SCIDDICA-SS_3 was calibrated against the 1997 Albano Lake (near Rome, Italy) event (Fig. 3a), which is a case of combined subaerial-subaqueous debris-flow [31]. This landslide occurred in the eastern slope of the Albano Lake on November 7th, 1997, after an intense rainfall event (128 mm in 24 hours) and began as a soil slide, mobilizing about 300 m^3 of fluvial 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 cubic metres at the coastline. A little amount of material was deposited at the coastline, while a greater quantity entered into water generating a little tsunami wave. Simulations permitted to verify the general model and to calibrate adequately its parameters.

In order to quantitatively evaluate the simulation outcome, experiments are compared with real cases by considering the following indicator e:

$$e = \sqrt{\frac{R \cap S}{R \cup S}}$$

where R is the set of cells affected by the landslide in the real event and S the set of cells affected by the landslide in the simulation. The fitness function, e, considers a normalized value between 0 (complete failure) and 1 (perfect simulation). Simulations are judged "acceptable" only when the indicators show values not exceeding prefixed thresholds of acceptability, fixed on the base of empirical considerations (as commonly performed in statistical analysis). In the case of the Albano landslide, such value is 0.7. The simulation carried out with the SS_3 model, and presented here (Fig. 5a, b) has a value of e equal to 0.83, which represents a very good, though preliminary, result.

The simulation made with SCIDDICA-SS_3 is quite similar to that made with the previous model [18], both with regard to the areal extent (Fig. 5a) and concerning the mass of mobilized material, which has decreasing thickness values from the release area until the beginning of accumulation zone (Fig. 5b) and, finally, even as regards the thickness of eroded soil during the passage of the landslide (Fig. 5c).

The substantial difference that emerges comparing the simulation carried out with SS_3 with the one made with the SS_2 model (cf. [18]) is the management of the landslide detachment area. In fact, in the SS_3 model the emptying effect of the detachment area is rather quick, contrary to the SS_2 model where this area was unable to completely empty until the end of the simulation, as a result showing a less compact landslide front. Moreover, the subaqueous path in SS_3 is better centred than in SS_2 in comparison with the real path because of the improved approximation due to the new inertial effects management.

Further refinements of the parameters could lead, therefore, for a better fitness as well as to speed up the propagation times, whose behaviour can be observed in the graph of Fig. 6.

Another feature of SCIDDICA-SS_3 is the possibility to insert along the path of the landslide deviation or containment works (retaining walls, bridge piers, etc.) to observe the effect of obstacles on the phenomenon development. For this purpose,

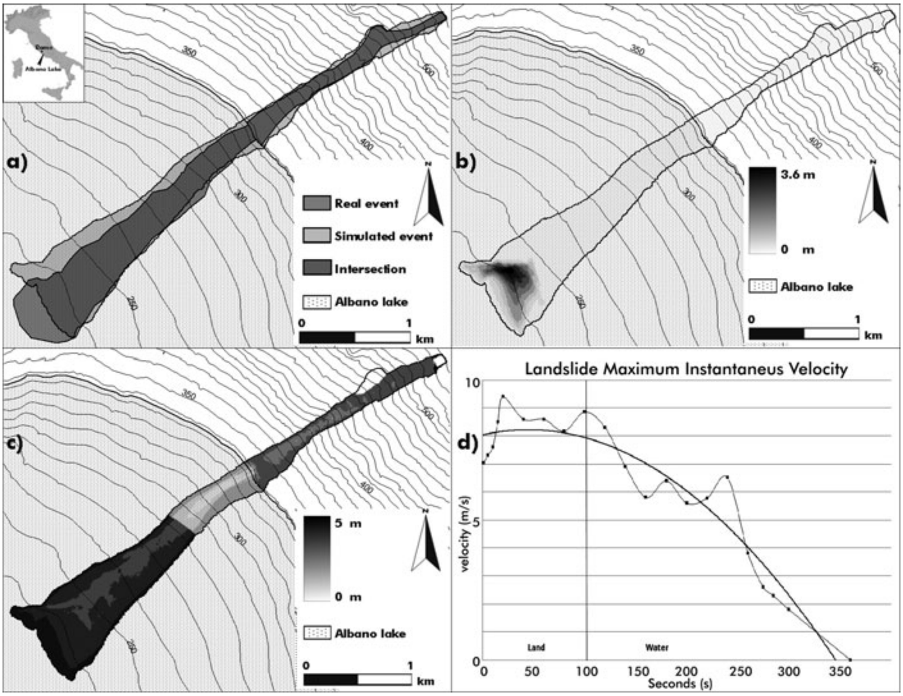

Fig. 5 The 1997 Albano Lake subaerial-subaqueous debris flow. (**a**) Intersection between real and simulated event; (**b**) Deposit thickness; (**c**) Erosion depth; (**d**) Maximum instantaneous velocity of the debris flow referred to the 1997 Lake Alban simulation. Results refer to the best performed simulation. The *thick contour line* represents the water level

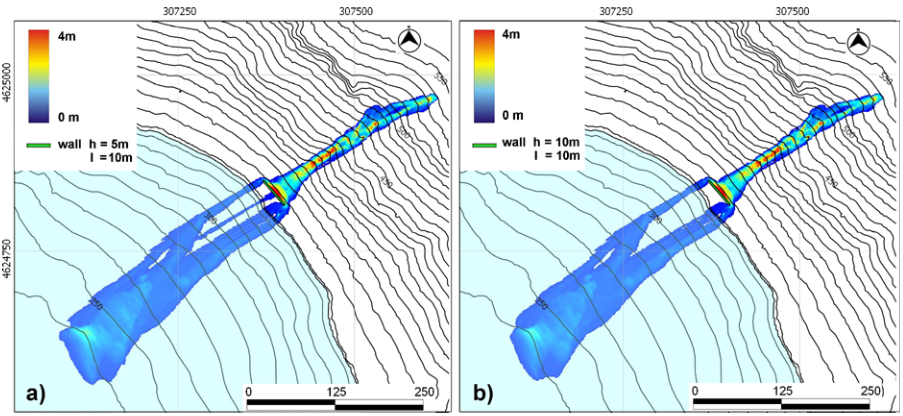

Fig. 6 Simulations carried out for evaluating the interactions of diversion and containment works, referred to the 1997 Lake Albano event. (**a**) Simulation with the inclusion of a 10-m long and 4-m high wall. (**b**) Simulation with the inclusion of a 10-m long and 9-m high wall

containment walls along the path of the landslide have been placed and a new simulation re-launched, the effects of which can be observed in Fig. 6a, b. By considering the same length of the walls, the lower one has been overcome by a small amount of detritus.

5 Conclusions and future outlook

SCIDDICA-SS_3 seems to capture fundamental instances of modelling surface flow with regard to conservation laws of physics according to a less empirical approach. Results of first simulations are satisfying, even if more controls and applications to different cases in need and parameters must be better tuned.

Future research work directions are: coupling of different elementary processes have to be improved, parameters have to be introduced independently of *CA* time-step and cell dimension by an opportune formulation of the transition function.

Such future research will permit to extend a methodology to other phenomena involving surface flows as snow avalanche, pyroclastic flows, soil erosion and coastal erosion.

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