Modelling Combined Subaerial-Subaqueous Flow-Like Landslides by Cellular Automata

Maria Vittoria Avolio[1], Valeria Lupiano[1,2], Paolo Mazzanti[3], and Salvatore Di Gregorio[1]

[1] University of Calabria, Department of Mathematics, 87036 Rende (CS), Italy
{avoliomv,dig}@unical.it
[2] University of Calabria, Department of Earth Sciences, 87036 Rende (CS), Italy
lupianov@unical.it
[3] University of Rome "La Sapienza", Department of Earth Sciences, P.le Aldo Moro, 00185, Roma, Italy
paolo.mazzanti@uniroma1.it

Abstract. Macroscopic Cellular Automata characterize a methodological approach for modelling large scale (extended for kilometres) complex acentric phenomena, e.g. surface flows as lava flows, debris flows etc.. This paper concerns the extension of such a method in order to simulate combined subaerial-subaqueous flow-like landslides. The occurrence of heterogeneous interacting processes requires a more physical description of the energy balance and an explicit velocity management. The model SCIDDICA-SS2 proposes some empirical solutions, such as the computation at each step and inside each cell, of departing flows which are characterized by their mass centre position and velocity. An application to combined subaerial-subaqueous landslide is exhibited together with simulation results of the 1997 Albano lake (Rome, Italy) debris flow.

1 Introduction

An extension of classical Cellular Automata (*CA*), the Macroscopic *CA* [1], were developed in order to model many complex macroscopic fluid-dynamical phenomena, that seem difficult to be modelled in other *CA* frames (e.g. the lattice Boltzmann method), because they take place on a large space scale.

Macroscopic *CA* can need a large amount of states, that describe properties of the cells (e.g. temperature); such states may be formally represented by means of substates, that specify the characteristics to be attributed to the state of the cell and determining the *CA* evolution. The Cartesian product of the sets of all substates constitutes the set of states. It involves a large amount of states more a complicated transition function, not reducible to a lookup table.

In the case of surface flows, quantities concerning the third dimension, i.e. the height, may be easily included among the *CA* substates (e.g. the altitude), permitting models in two dimensions, working effectively in three dimensions. Furthermore, an algorithm for the minimisation of the differences (in height) [1] was found in this context in order to determine the outflows from a cell

H. Umeo et al. (Eds): ACRI 2008, LNCS 5191, pp. 329–336, 2008.

toward the remaining cells of its neighbourhood, giving rise to several models for different macroscopic phenomena: lava flows [1], debris/mud flows [1] and rain soil erosion [2].

This empirical method has a significant restriction, because it doesn't permit to make velocity explicit with a radius 1 neighbourhood: 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 "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 space (i.e. considering clusters of cells) or by averaging on the time (e.g. considering the advancing flow front average velocity in a sequence of *CA* steps).

Constant velocity could be a limit for modelling finely macroscopic phenomena, because it is difficult sometime 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: 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. This overall method was applied first to lava flows [3]; the extension to debris flows involved more complex criteria to be considered.

The next section defines the criteria, adopted in modelling combined subaerial-subaqueous debris flows i.e. SCIDDICA-SS2, the simulation results of the 1997 Albano lake (Rome, Italy) debris flows [4] are shown in the third section, conclusions are reported at the end.

2 A *CA* Model for Combined Subaerial-Subaqueous Flow-Like Landslides

CA represent an alternative to differential equations for complex systems evolving by local interactions. Some researchers proposed *CA* models for flow type landslides.

Di Gregorio et al. [5] developed a simple two-dimensional *CA* model (first release of SCIDDICA) and validated it by simulating the Mt Ontake landslide. Many extensions of SCIDDICA were afterwards developed in order to improve the model and/or capture the characteristics of different or more complex landslides, performing also susceptibility analysis [6,7,8,9].

Segre and Deangeli [10] 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 [11] simulated the Corniglio landslide using a simple *CA* model in order to capture the blockage mechanisms for that type of landslide.

Salles et al. [12] developed recently a first interesting *CA* model for subaqueous flows, in order to simulate density currents.

2.1 The Model SCIDDICA-SS2

This version of SCIDDICA is an extension of the model applied to the landslides of Sarno [8] improved by the method of explicit velocities of the SCIARA model [3]. Such an extension involves more substates, processes and parameters because the phenomenon is more complex: in fact, subaqueous part of Albano landslide needs to be first modelled, especially the air-water transition.

The hexagonal *CA* model SCIDDICA-SS2 is the quintuple $< R, X, S, P, \tau >$:

- R is the set of regular hexagons covering the region, where the phenomenon evolves.
- X identifies the geometrical pattern of cells, which influence any state change of the central cell: the central cell (index 0) itself and the six adjacent cells (indexes 1,...,6).
- S is the finite set of states of the finite automaton, embedded in the cell; it is equal to the Cartesian product of the sets of the considered substates:

$$S = S_A \times S_D \times S_{TH} \times S_X \times S_Y \times S_{KH} \times S_E^6 \times \\ \times S_{XE}^6 \times S_{YE}^6 \times S_{KHE}^6 \times S_I^6 \times S_{XI}^6 \times S_{YI}^6 \times S_{KHI}^6$$

  - S_A is the cell altitude, S_D is the maximum depth of detrital cover, that could be transformed by erosion in landslide debris;
  - S_{TH} is the average thickness of landslide debris inside the cell, S_X and S_Y are the co-ordinates of the debris barycentre with reference to the cell centre, S_{KH} is the debris kinetic head;
  - S_E is the part of debris flow, the so called "external flow", (normalised to a thickness) that penetrates the adjacent cell from central cell, S_{XE} and S_{YE} are the co-ordinates of the external flow barycentre with reference to the adjacent cell centre, S_{KHE} is the debris kinetic head (six components for all the substates);
  - S_I is the part of debris flow toward the adjacent cell, the so called "internal flow", (normalised to a thickness) that remains inside the central cell, S_{XI} and S_{YI} are the co-ordinates of the internal flow barycentre with reference to the central cell centre, S_{KHI} is the debris kinetic head (six components for all the substates).
- P is the set of the global physical and empirical parameters, which account for the general frame of the model and the physical characteristics of the phenomenon; the next section provides a better explication of the elements in the following list:

$$P = \{p_a, p_t, p_{adhw}, p_{adha}, p_{fcw}, p_{fca}, p_{tdw}, p_{tda}, \\ p_{edw}, p_{eda}, p_{ml}, p_{mtw}, p_{mta}, p_{pew}, p_{pea}, p_{wr}\}$$

  - p_a is the cell apothem; p_t is the temporal correspondence of a *CA* step;
  - p_{adhw}, p_{adha} are the water/air adhesion values, i.e. the debris thickness, that may not removed;
  - p_{fcw}, p_{fca} are the water/air friction coefficient for debris outflows;

  - p_{tdw}, p_{tda}, p_{edw}, p_{eda} are water/air parameters for energy dissipation by turbulence, water/air parameters for energy dissipation by erosion;
  - p_{ml} is the matter loss in percent when the debris enters into water;
  - p_{mtw}, p_{mta} are the water/air activation thresholds of the mobilisation;
  - p_{tmt}, is the activation threshold of the mobilisation for the transept;
  - p_{pew}, p_{pea} are the water/air progressive erosion parameters;
  - p_{wr} is the water resistance parameter.
- $\tau : S^7 \rightarrow S$ is the deterministic state transition for the cells in R. The 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, S_A assumes the morphology values except for the detachment area, where the thickness of the landslide mass is subtracted from the morphology value; S_{TH} is zero everywhere except for the detachment area, where the thickness of landslide mass is specified; S_D assumes initial values corresponding to the maximum depth of the mantle of detrital cover, which can be eroded; 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 R, so that the configuration changes in time and the evolution of the CA is obtained.

2.2 The SCIDDICA-SS2 Transition Function

Four local processes may be considered for the release SS2 of SCIDDICA:

- altitude, kinetic head, debris thickness variation by detrital cover erosion;
- 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.

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. Variables concerning substates and parameters are indicated by their abbreviation. When substates need the specification of the neighbourhood cell, its index is indicated between square brackets. ΔQ means variation of the substate S_Q. Parameter final letter (w, a) is omitted when the formula is valid both in water and air.

Mobilisation Effects. When the kinetic head value overcomes an opportune threshold ($KH > mt$) depending on the soil features and its saturation state then a mobilisation of the detrital cover occurs proportionally to the quantity overcoming the threshold: $pe \cdot (KH - mt) = \Delta TH = -\Delta D$ (the detrital cover depth diminishes as the debris thickness increases), the kinetic head loss is: $-\Delta KH = ed \cdot (KH - mt)$. 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, it implicates trivially a further kinetic head reduction.

The activation of secondary sources is managed by a "transept" for each secondary source. A threshold *tmt* for the thickness of the debris flow crossing the transept is specified and secondary soil slips are actived for $TH > tmt$.

Turbulence Effect. The effect of the turbulence is modelled by a proportional kinetic head loss at each SCIDDICA step: $-\Delta KH = td{\cdot}KH$. 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.

Debris Outflows. Outflows computation is performed in two steps: determination of the outflows minimising the "height" differences in the neighbourhood [1] and determination of the shift of the outflows.

Rapid debris flows imply often a run up effect, depending on the kinetic head associated to debris flow. As a consequence, the height minimisation algorithm [1] is applied, considering for the central cell the fixed part $b[0] = A[0]+KH[0]+adh$ and the movable (distributable) part $m[0] = TH[0]-adh$. The fixed part for the adjacent cells is: $b[i] = A[i] + TH[i]$, $1 \leq i \leq 6$; note that $KH[0]$ accounts for the ability of the flowing debris of climbing a slope. The minimisation algorithm determines the flows $f[i]$, $0 \leq i \leq 6$ toward the neighbouring cells ($f[0]$ is the part of $m[0]$ which is not distributed); such flows minimise the expression: $\sum \mid (b[i] + f[i]) - (b[j] + f[i]) \mid$ for $\{(i, j) \mid 0 \leq i < j \leq 6\}$.

The barycentre co-ordinates x and y of moving quantities are the same of all the debris 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 the friction effects, that prevent debris outflows, when the difference in height, $b[0] + m[0] - b[i]$, that determines an ideal slope "$\theta[i]$" between the two cells 0 and i, is insufficient: the condition is expressed by the formula $\tan\theta[i] < fc$. A ideal distance "d" 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: $sh = v{\cdot}t + g(\sin\theta - fca{\cdot}\cos\theta)t^2/2$, with "$g$" the gravity acceleration, the 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: $sh = = (1 - exp(-wr \cdot t))(v - (g(\sin\theta - fcw \cdot \cos\theta)/wr)) + g(\sin\theta - fcw \cdot \cos\theta) \cdot t/wr$.

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 barycentres corresponding to the barycentres of the internal debris flow and the external debris flow. Kinetic head variation is computed according to the new position of internal and external flows, while 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 left 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 X and Y considering remaining debris in the central cell, internal flows and inflows.

Air-Water Interface. Air-water interface is managed only for external flows from air to water and not vice versa. 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 ml, it implies a correspondent loss of kinetic energy, determined by kinetic head decrease.

3 Simulations of the 1997 Albano Lake Debris Flow

SCIDDICA-SS2 was validated against the 1997 Albano lake (Rome, Italy) event (fig. 1) which is a rare case of combined subaerial-subaqueous debris-flow [4]. 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 m^3 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 m^3 at the coastline. A few amount of material was deposited at the coastline while a greater quantity entered in water generating a little tsunami wave.

Detailed subaerial and submerged topographic data was acquired in 2005 and 2006 through aerial LiDAR and sonar multibeam swath bathymetric surveys, performed by the INGV (Italian National Institute of Geophysics and Volcanology) in the frame of a project sponsored by the Italian National Civil Protection Department. Consequently, a 1m cell size DTLM (Digital Terrain and Lacustrine Model) was produced and allowed to map in detail both the subaerial and the submerged detachment and deposition areas and to estimate their volumes [4].

Simulations permit to validate the general model and to calibrate adequately its parameters; results show a good agreement concerning erosion and deposits on both subaerial and subaqueous part (fig. 2). A partial, but very significant (quantitative) comparison between the real event and the simulated one for both the environments may be performed by a fitness function $\boldsymbol{f}$, that considers a normalised value between 0 (complete failure) and 1 (perfect correspondence), computed by the following formula $\sqrt{((\boldsymbol{R} \cap \boldsymbol{S})/(\boldsymbol{R} \cup \boldsymbol{S}))}$, where $\boldsymbol{R}$ is the set

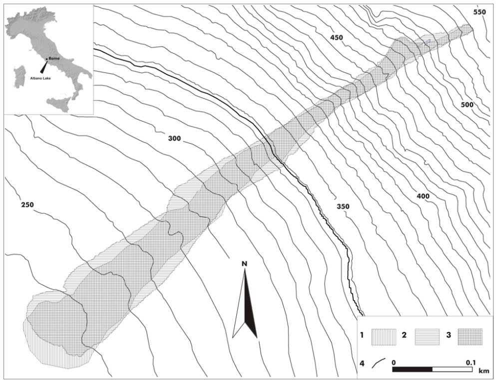

Fig. 1. The 1997 Albano lake subaerial-subaqueous debris flow. Key: (1) real event, (2) simulated event, (3) intersection between real and simulated event, (4) water level.

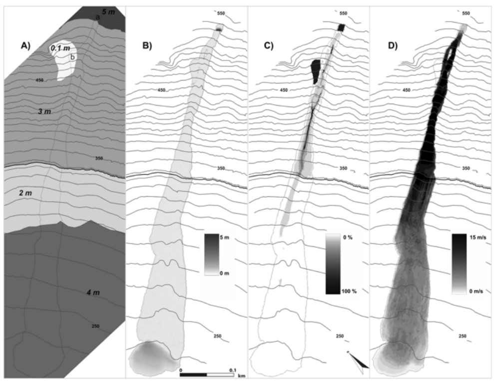

Fig. 2. A) regolith thickness (value is in italic) with pre-event reconstructed contour lines; "a" and "b" respectively principal and secondary source. The results regarding the best simulation are shown: B) deposit thickness; C) erosion depth; D) max occurred velocity. The thick contour line represents the water level.

of cells affected by the landslides in the real event and $\boldsymbol{S}$ the set of cells affected by the landslides in the simulation.

We obtain an encouraging $\boldsymbol{f}$ value 0.85 (fig. 1), that confirms a satisfying reliability in reproducing the phenomenon. The performance is positive compared to results of other models, that use almost more qualitative than quantitative evaluation tools.

4 Conclusions

Simulations of the 1997 Albano lake debris flow proved to be consistent with the observed path, deposit and erosion of the actual landslide suggesting that

SCIDDICA-SS2 could be usefully used in hazard analyses for subaerial, subaqueous and combined flow-like landslides; applications to other cases are planned.

SCIDDICA-SS2 is the first model for subaerial-subaqueous flow-like landslides (there are many only-subaerial models and few only-subaqueous models) to our knowledge. The problematical air-water transition gave rise to significant improvements in comparison with other SCIDDICA versions, i.e. the introduction of the explicit velocity with a more precise computation of shift for internal and external flows, while a limit is a possible underestimation of inertial effects.

Acknowledgments. This research was funded by the Italian Government, MIUR, PRIN-06, 2006042319, Project "Integration of inshore and offshore geological and geophysical innovative techniques for coastal landslides studies".

References

1. Di Gregorio, S., Serra, R.: An empirical method for modelling and simulating some complex macroscopic phenomena by cellular automata. Future Generation Computer Systems 16, 259–271 (1999)
2. D'Ambrosio, D., Di Gregorio, S., Gabriele, S., Gaudio, R.: A cellular automata model for soil erosion by water. Physics and Chemistry of the Earth - Part B 26, 33–39 (2001)
3. Avolio, M.V., Crisci, G.M., Di Gregorio, S., Rongo, R., Spataro, W., Trunfio, G.A.: SCIARA $\boldsymbol{\gamma}$**2**: an improved cellular automata model for lava flows and applications to the 2002 Etnean crisis. Computers & Geosciences 32, 897–911 (2006)
4. Mazzanti, P., Bozzano, F., Esposito, C.: Submerged landslides morphologies in the Albano lake (Rome, Italy). In: Lykousis, V., Sakellariou, J.L.D. (eds.) Proc. of 3rd Intern. Symp. Submarine Mass Movements and Their Consequences, Lugano, Switzerland, 2007. Advances in Natural and Technological Hazards Research, vol. 27, pp. 243–250. Springer, Heidelberg (2007)
5. Di Gregorio, S., Nicoletta, F., Rongo, R., Sorriso-Valvo, M., Spezzano, G., Talia, D.: Landslide simulation by cellular automata in a parallel environment. In: Furnari, M.M. (ed.) Proceedings of 2nd International Workshop Massive Parallelism: Hardware, Software and Applications, pp. 392–407. World Scientific, Singapore (1995)
6. Di Gregorio, S., Rongo, R., Siciliano, C., Sorriso-Valvo, M., Spataro, W.: Mt. Ontake landslide simulation by the cellular automata model SCIDDICA-3. Physics and Chemistry of the Earth 24, 97–100 (1999)
7. Avolio, M.V., Di Gregorio, S., Mantovani, F., Pasuto, A., Rongo, R., Silvano, S., Spataro, W.: Simulation of 1992 Tessina landslide by a cellular automata model and future hazard scenarios. JAG 2, 41–50 (2000)
8. D'Ambrosio, D., Di Gregorio, S., Iovine, G.: Simulating debris flows through a hexagonal cellular automata model: SCIDDICA S3-hex. NHESS 3, 545–559 (2003)
9. Iovine, G., D'Ambrosio, D., Di Gregorio, S.: Applying genetic algorithms for calibrating a hexagonal cellular automata model for the simulation of debris flows characterised by strong inertial effects. Geomorphology 66, 287–303 (2005)
10. Segre, E., Deangeli, C.: Cellular automaton for realistic modelling of landslides. Nonlinear Processes in Geophysics 2, 1–15 (1995)
11. Clerici, A., Perego, S.: Simulation of the Parma river blockage by the Corniglio landslide (Northern Italy). Geomorphology 33, 1–23 (2000)
12. Salles, T., Lopez, S., Cacas, M.C., Mulder, T.: Cellular automata model of density currents. Geomorphology 88, 1–20 (2007)