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Simulation of the 1992 Tessina landslide by a cellular automata model and future hazard scenarios

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ABSTRACT

Cellular Automata are a powerful tool for modelling natural and artificial systems, which can be described in terms of local interactions of their constituent parts. Some types of landslides, such as debris/mud flows, match these requirements. The 1992 Tessina landslide has characteristics (slow mud flows) which make it appropriate for modelling by means of Cellular Automata, except for the initial phase of detachment, which is caused by a rotational movement that has no effect on the mud flow path. This paper presents the Cellular Automata approach for modelling slow mud/debris flows, the results of simulation of the 1992 Tessina landslide and future hazard scenarios based on the volumes of masses that could be mobilised in the future. They were obtained by adapting the Cellular Automata Model called SCIDDICA, which has been validated for very fast landslides. SCIDDICA was applied by modifying the general model to the peculiarities of the Tessina landslide. The simulations obtained by this initial model were satisfactory for forecasting the surface covered by mud. Calibration of the model, which was obtained from simulation of the 1992 event, was used for forecasting flow expansion during possible future reactivation. For this purpose two simulations concerning the collapse of about 1 million m^3 of material were tested. In one of these, the presence of a containment wall built in 1992 for the protection of the Tarcogna hamlet was inserted. The results obtained identified the conditions of high risk affecting the villages of Funes and Lamosano and show that this Cellular Automata approach can have a wide range of applications for different types of mud/debris flows.

INTRODUCTION

A debris/mud flow can be physically described by fluid-dynamics equations and can range rheologically from approximately Newtonian liquids to brittle solids [Johnson, 1973]. When simulations are based on differential equation methods of solution, forecasting the development of a debris/mud flow may meet serious difficulties, since it is extremely arduous to solve the governing flow equations, especially when rheological behaviour can range from plastic to highly liquid flow [Sassa, 1988].

In this paper an alternative approach is presented: that of Cellular Automata (CA), a main paradigm of Parallel Computing that can be easily implemented on Parallel Machines [Di Gregorio *et al*, 1995]. CA models can be easily applied to a-centric systems, *ie,* systems distributed in a space, which may be described as evolving exclusively on the basis of the local interactions of their constituent parts.

CA models for simulation of debris/mud flow were developed by our research group [Di Gregorio *et al*, 1995; Di Gregorio *et al*, 1999] with the two-dimensional CA SCIDDICA (Smart Computational Innovative method for the Detection of Debris/mud flow path with Interactive Cellular Automata, to be read as "she'ddekah") and by Segre & Deangeli [1995] with a three-dimensional CA model.

The approach of Segre & Deangeli [1995] comprised an ingenious transposition of a system of differential equations expressed in terms of CA, very similar to some numerical methods of the finite differences type. The implementation of their method involves a great deal of computational resources if satisfactory precision is to be obtained. They applied their method to the simulation of the landslide of Mount XiKou in China with good results [Segre & Deangeli, 1995].
SCIDDICA is based on a different approach, which is described in following section of this paper (Methodological approach). The first validation of SCIDDICA was tested in several ways on the Mount Ontake landslide [Di Gregorio *et al*, 1995; Di Gregorio *et al*, 1999]: the real flow field and the simulated flow field show strikingly similar shapes for the Ontake landslide.

The 1992 Tessina landslide [Pasuto *et al*, 1992; Angeli *et al*, 1994] has physical characteristics very different from those of Mount Ontake [Sassa, 1988]. Its rheological behaviour is less complex because there is no run-up effect in the Tessina landslide. Therefore a model for the Tessina landslide was obtained by a simplification of the model used for Mount Ontake. Such a simplification is not trivial because it optimises the model, taking into account the peculiarities of the Tessina mud flows.

METHODOLOGICAL APPROACH

A homogeneous CA may be considered as a d-dimensional Euclidean space: a cellular space partitioned into cells of uniform size, each one embedding an identical finite automaton, the so-called elementary automaton (EA).

When a CA model models natural macroscopic phenomena, the cell usually corresponds to a portion of physical space, and the EA state of the cell accounts for the relevant characteristics of that portion of space. It is therefore natural to assume that the cellular space is at most three-dimensional, as in some cases symmetry or homogeneity considerations allow a reduction to two or one dimension. Two-dimensional CA may support surface phenomena (*eg,* mud/debris flows) when the EA state accounts for the third dimension.

Input for each EA is given by the states of the EA in the neighbouring cells, where neighbourhood conditions are determined by a pattern invariant in time and constant over the cells. At time $t = 0$, EA are in arbitrary states and the CA evolve by changing the state of all EA simultaneously at discrete times, according to the transition function of the EA. Each transition (change of the states of the CA) corresponds to a step of the CA.

DEFINITION OF CELLULAR AUTOMATA

We introduce an extension of the definition of homogeneous CA, the primary and main class of CA, which is (to our knowledge) most commonly used in modelling and simulation. Such an extension is useful in order to model macroscopic phenomena [Di Gregorio & Serra, 1999]. The CA is defined:

$$CA = \langle R, X, Q, P, \sigma \rangle$$

R is a finite cellular d-dimensional region where the phenomenon evolves; it is defined by means of a d-dimensional vector of integers $l = \langle l_1, l_2, \ldots l_d \rangle$, which denotes the limits of this finite region; then $R = \{i = \langle i_1, i_2, \ldots i_d \rangle | 0 \leq i_1 \leq l_1, 0 \leq i_2 \leq l_2, \ldots 0 \leq i_d \leq l_d\}$ with $i_1, i_2, \ldots i_d$ integers. R is chosen so large that there is no evolution at its borders. The cells are squares and cubes, respectively, for two-dimensional and three-dimensional CA.

X, the neighbourhood index, is a finite set of d-dimensional vectors which defines the set N(X,i) of neighbours of cell $i = \langle i_1, i_2, \ldots i_d \rangle$ as follows: let $X = \{x_0, x_1, \ldots x_{m-1}\}$ with $m = \#X$, $N(X,i) = \{(i+x_0),(i+x_1),\ldots(i+x_{m-1})\}$. x_0 is always the null vector and identifies the cell itself; the cells with a coordinate $0, l_1, l_2, \ldots l_d$, at least, do not have a complete neighbourhood. Usually a neighbourhood is chosen for a two-dimensional CA such that two cells are defined as neighbouring cells when they have a common edge. A usual neighbourhood for a three-dimensional CA is such that two neighbouring cells have a common face.

Q is the finite set of states of the EA.

P is the finite set of global parameters of the CA.

$\sigma: Q^m \rightarrow Q$ is the transition function of the EA; σ is not applied to cells without complete neighbourhood.

$C = \{c | c: R \rightarrow Q\}$ is the set of possible state assignments to the cells of R and will be called the set of configurations; c(i) is the state of cell i.

Let c(N(X,i) be the ordered set of states of the neighbourhood of i. Then the global transition function τ is defined by $\tau: C \rightarrow C$ is such that $[\tau(c)](i) = \sigma(c(N(X,i)))$

When τ is not determined through constant σ and X, then the CA is not homogeneous.

When appropriate, the previous definition may be easily extended to different tessellations, *eg*, hexagonal, triangular tessellation in a two-dimensional space, which can be easily reduced to the square one.

Two global parameters must be always considered: the size of the cell and the clock of the CA (*ie,* the physical time corresponding to a CA step); they usually effect the transition function implicitly.

Each characteristic, relevant to the evolution of the system and relative to the portion of the space corresponding to the cell, is defined as a substate. The allowed values of the substate form a finite set. The set of possible states of the cell is given by the Cartesian product of the sets of substates, *ie,* $Q = Q_1 \times Q_2 \times \ldots \times Q_n$.

We made a first assumption that the values of the substates (*eg,* the temperature) are constant in the space occupied by the cell.

The change of each substate in the cell can be caused by internal transformations $T_1, T_2, \ldots T_p$ and/or local interactions with the neighbourhood $I_1, I_2, \ldots I_q$. Internal transformations are defined as the changes in the values of the substates due to interactions among substates inside the cell or due simply to the elapse of time.

A function $\sigma_{Ti}: Q_{Ti1} \rightarrow Q_{Ti2}$ is defined for each internal transition T_i, $1 \leq i \leq p$, where $Q_{Ti1}, Q_{Ti2} \in \wp(Q)$, which is the power set of Q.

The second assumption prescribes that the interactions in the neighbourhood (local interactions) must/may be described in terms of flows of some quantity in the central cell (expressed as a substate) towards its neighbours in order to reach equilibrium conditions or to reduce conditions of imbalance, so an opportune law and a relaxation rate must be determined. This assumption might seem very restrictive but in many cases the problem can be easily reduced to the minimisation of the differences of a certain quantity in the neighbourhood.

When the minimisation of the differences is applied, the extent of non-equilibrium conditions will be reduced. At each time step, the relaxation rate and the size of the CA time step must be properly chosen in order to describe the actual relaxation kinetics of the macroscopic system.

A function σ_{Ij}: $Q_{Ij1}{}^{m} \rightarrow Q_{Ij2}$ is defined for each interaction I_j, $1 \leq j \leq q$, where $Q_{Ij1}, Q_{Ij2} \in \wp(Q)$, the corresponding relaxation rates r_j must be also fixed. The relaxation rate is a parameter of the CA.

The third assumption is that the fragmentation of the complex phenomenon in internal transformations and local interactions may be applied, calculating sequentially the change of the values of the substates. This assumption is the most critical one because it cannot be always deduced *a priori*, although in any case it can be tested in the phase of validation of the model. It often works only under a specific range of conditions of the phenomenon.

The new value of Q_k at the time t+1 is obtained starting from the values of the substate at the time t and adding the variations Δk_1, Δk_2, ...Δk_p that are determined by the transformations and the flows fk_1, fk_2, ...fk_q determined by the interactions.

ALGORITHM OF THE MINIMISATION OF THE DIFFERENCES

An outline of the algorithm of the minimisation of the differences is given here in a simplified version; the input data are the values at step t of a positive quantity *q[i]*, $0 \leq i < m$ for each cell *i* of the neighbourhood.

p is a positive quantity, associated to the central cell, that can be distributed to the neighbours; the *p* distribution creates the positive flows *f[i]*, $0 \leq i < m$ (*f[0],* is the quantity of *p* which remains in the central cell):

$$p = \sum_{i=0}^{m-1} f[i]$$

q'[i] = q[i] + f[i], $0 \leq i < m$, is obtained after the distribution and *q'_min* is the minimum value of *q'[i]* in the neighbourhood after the *p* distribution; the flows *f[i]*, $0 \leq i < m$, must be determined so that the following expression must be minimised:

$$\sum_{i=1}^{m-1} (q'[i] - q'\_min)$$

This expression was chosen because it represents in a discrete a-central context the best condition for performing in the cellular space a distribution that minimises the differences. The neighbours, towards which the flow is null, are initially selected considering *average*:

$$average = (p + \sum_{i=0}^{m-1} q[i]) / m$$

A *q[i]* greater than average indicates that a flow towards *i* is impossible, so *i* must be eliminated from the distribution and from the computation of the new next value of *average*.

This computation is re-iterated using the remaining cells, calculating the new *average* and eliminating cells for which *q[i]* is greater than the *average* until there are no more cells to be eliminated. Eventually the difference between the last calculated *average* and *q[i]* for the cells not eliminated represents the new inflow value to the neighbour cell *i*.

The following instructions sketch the algorithm:
(a) *A* is the set of cells not eliminated. Its initial value is set to the number of its neighbours.
(b) The *average* height is found for the set *A* of non-eliminated cells:

$$average = (p + \sum_{i \in A} q[i]) / \# A$$

(c) The cells with height larger than the average height are eliminated from *A*.
(d) Go to step (b) until no cell is to be eliminated.
(e) The flows, which minimise the height differences locally, are such that the new height of the non-eliminated cells is the value of the *average* height.
For the example of a two-dimensional CA where p = 10, q[0] = 7, q[1] = 30, q[2] = 7, q[3] = 13, q[4] = 3, the flows f[i] from the central cell are determined as shown in Figure1.

A flow rate in the CA discrete context must be considered in a special way. The directions of the flows are only m-1 (the number of the neighbours except the central cell). Only two values of velocity may apparently exist: 0 and the constant value, obtained from the cell edge divided by the time corresponding to a step of the CA. The destiny of an initial quantity *q* present in the cell may be recognised only after many steps, considering the cells where *q* has been distributed.

The flows, which have been computed, permit the maximum local equilibrium, *ie,* they minimise the differences. The relaxation is a parameter which "cuts" the flows.

The cutting is obtained by dividing the values of the flows by this parameter. When the relaxation value is 1, the maximum local equilibrium is reached in a CA step; a value of the relaxation parameter larger than 1 imposes a sort of obstacle to reaching the local equilibrium in a CA step. It may account for forces that delay the flows.

CA MODEL SCIDDICA FOR THE TESSINA LANDSLIDE

The cellular automaton model is the quintuple

SCIDDICA = <R, X, Q, P, σ>, where

R = {(x, y)|x,y∈ *N*, $0 \le x \le l_x$, $0 \le y \le l_y$} is the set of points with integer coordinates in the finite region, where the phenomenon evolves. *N* is the set of natural numbers.

The set X identifies the geometrical pattern of cells which influence the cell state change. They are, respectively, the cell itself and the "north", "south", "east" and "west" neighbouring cells:

X = {(0,0), (0,1), (0,-1), (1,0), (-1,0)};

This neighbouring arrangement was chosen because it assures the same minimum distance and the same spatial relation between the central cell and each neighbour.

The finite set Q of states of the fa:

$Q = Q_a \times Q_{th}$

where substates are:

Q_a correlated to the altitude of the cell;

Q_{th} correlated to the thickness of mud material in the cell.

The elements of Q_a are integers that express the value of the altitude (dm); the elements of Q_{th} are integers that represent the material quantity inside the cell, expressed as thickness in dm.

P is the set of the global parameters, which accounts for the general frame of the phenomenon and the characteristics of the mud flow. They are:

p_c the edge of the cell;

p_t the temporal correspondence of a step of SCIDDICA;

p_a the adherence;

p_f the friction angle;

p_r the relaxation rate.

s: $Q^5 \rightarrow Q$ is the deterministic state transition for the cells in R, which will be outlined in the next section.

Initial conditions are given by the morphology and by the determination of the detached area in terms of the mud thickness. At each following step, the function s is applied to every cell in R so that the configuration is changed in the time and the evolution of the CA is obtained.

MAIN CHARACTERISTICS OF σ

The transition function's main mechanism, specified by "σ_{I1}", computes "mud outflows" from the single cell toward the cells with common sides and updates the single cell's mud content.

The algorithm for the minimisation of the differences is applied in the following local interaction σ_{I1}.

σ_{I1}: $(Q_a \times Q_{th})^5 \rightarrow f_{th}{}^4$

where $f_{th}{}^4$ are the four possible outflows of mud (expressed in terms of mud thickness) from the central cell.

The values of the cell substates at time t+1 are calculated according to the values of neighbouring cell substates at time t. Indexes 0, 1, 2, 3, 4 are used for the cell itself (or central cell) and its neighbours "north", "east", "west", "south", respectively.

There is no altitude variation, because mud solidification is not considered. The mud thickness at step t+1 is given approximately by the thickness at step t to which is added mud inflows from the neighbour cells and from which is subtracted mud outflows to the neighbour cells. The specification of the computation of the outflows from a central cell to the neighbours is first discussed here; lastly, a Pascal-like procedure expresses unambiguously the adopted algorithm.

Because of the friction between mud mass and soil, as well as the friction internal of the mud mass itself, only a portion of the mud in the cell can be distributed [Johnson, 1973]. Therefore, it is assumed that flows can occur between the cell and the i-th neighbour only if the tangent of local slope angle between the cell and the i-th neighbour (*tan_theta[i]*) is larger than a coefficient of friction (*friction_coeff*), corresponding to a friction angle (Figure 2) and depending on the nature of the soil, type

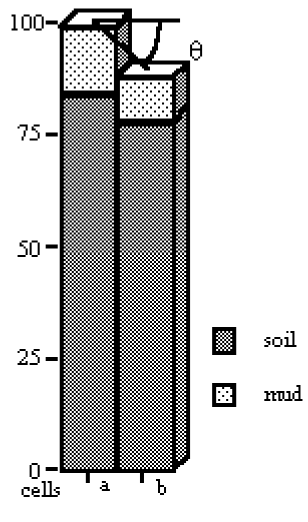

FIGURE 2: Local slope angle between two cells.

of mud and water content (the determination of the friction angle for the Tessina landslide is discussed in the *simulations* of the 1992 slide). In this way the neighbours (not *non-eliminated* cells) for which outflows are permitted are determined. The outflows depend on the hydrostatic pressure gradients due to differences in height (cell altitude plus mud thickness) between a cell and its four neighbours.

The maximum equilibrium conditions in a neighbourhood, where only the central cell may distribute mud to the neighbours, can be obtained by the minimisation of the difference of heights after the distribution. We compute the mud flows corresponding to these equilibrium conditions. Of course, equilibrium conditions cannot be reached instantaneously, so a *relaxation_rate* must be considered, according to the clock of the CA. Relaxation is described in terms of a parameter applied in the following way: the mud flows (which minimise the difference of height and represent the maximum possible equilibrium) are divided by this parameter, the results of which give the values of the mud outflows of the cell in a step of SCIDDICA. Mud can flow only if its thickness is larger than a threshold *adherence*, which accounts for the effects of friction. If the quantity of mud in the cell is small, then it adheres to the soil. Only when thickness overcomes adherence, may the *avail_mud* quantity, which is the difference between mud thickness and adherence, eventually be distributed.

The previous condition, "mud thickness larger than adherence", tests if mud outflows are possible. Another condition must be successively tested. The cells for which the mud cannot flow in are recognised initially by identifying neighbours with local slope angles whose tangents are smaller than the friction coefficient. The test of these two conditions is preliminary to the computation of the outflows of a cell, after which the algorithm of the minimisation of differences must be applied.

z[i] are given by altitude plus *adherence* for the central cell and altitude plus mud thickness for its neighbours. *A* is the set of non-eliminated cells. Later the average height, *av_height*, is computed according the following formula:

$$av\_height = (avail\_mud + \sum_{i \in A} z[i]) / \# A$$

z[i]' greater than *av_height* indicates that the mud cannot flow towards the cell *i*; so *i* must be eliminated from the distribution and from *av_height* computations.

This computation is re-iterated with the remaining cells, calculating the new *av_height* and eliminating cells with *z[i]* greater than *av_height* until there are no more cells to be eliminated; the quantity *av_height-z[i]* for the remaining neighbouring cells represents the mud inflow to the neighbouring cell *i*. It is divided by the *relaxation_rate* in order to compute the outflow.

The Pascal-like procedure in Figure 3 exactly specifies the algorithm.

1992 TESSINA LANDSLIDE

In April 1992 the Tessina landslide caused situations of great risk for two villages and adequate measures to safeguard people exposed to that risk had to be considered, in addition to the need to monitor and check the movement's evolution [Pasuto *et al*, 1992; Angeli *et al*, 1994].

The Tessina landslide, which was first triggered in October 1960, is a complex movement with a source area affected by rotational-translational slides in the upper sector; downhill the slide turns into a mud flow through a steep channel. The rock types involved in the landslide belong to the Flysch Formation (Eocene). It consists of a rhythmic alternation of marly-argillaceous and calcarenite layers about 1000-12000 m thick. The landslide developed in the Tessina valley between the altitudes of 1220 m and 625 m a.m.s.l., with a total longitudinal extension of nearly 3 km and a maximum width of about 500 m. The mud flow passed very close to the village of Funes and stretched downhill as far as the village of Lamosano (Figure 4).

During the 1960s several reactivations, involving about 5 million m^3 of material, occurred, causing the filling of the Tessina valley with displaced material 30-50 m thick. These movements seriously endangered the village of

```
procedure flow;
begin
  if thickness[0] > adherence then
    begin
      available_mud := thickness[0] - adherence;
      eliminated[0] := false;
      for i := 1 to 4  do
        eliminated[i] := tan(theta[i]) < friction_coeff;
      repeat
        new_control := false;
        z_sum := available_mud;
        count := 0;
        for i := 0 to 4  do
          if not eliminated[i] then
            begin
              z_sum := z_sum + z[i];
              count := count + 1
            end;
        av_height:= z_sum / count;
        for i := 0 to 4  do
          if (z[i] > av_height) and (not eliminated[i]) then
            begin
              new_control := true;
              eliminated[i] := true
            end
      until not new_control;
      for i := 1 to 4 do
        if eliminated[i] then
          outflow[i] := 0
        else
          outflow[i] := (av_height - z[i]) / relaxation_rate;
    end
end;
```

FIGURE 3: Pascal-like procedure for computing the cell outflows.

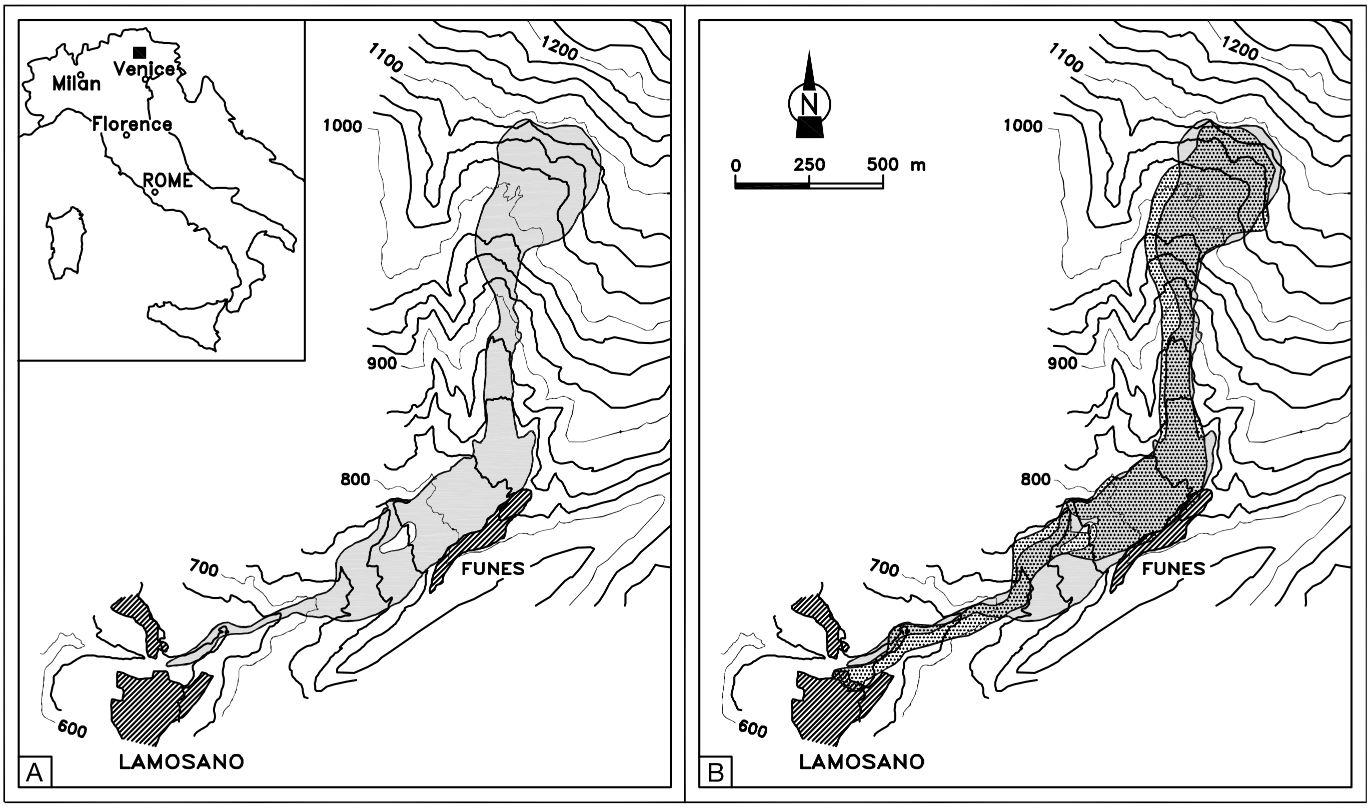

FIGURE 4: (A) Areal distribution of the landslide material during the 1992 event and (B) comparison between the real event and the simulated one (see also Figure 5).

Funes, which is situated on a steep ridge – originally quite high above the river bed, but now at nearly the same level as the mud flow.

The collapsed sector of the April 1992 event occupies an area 40,000 m^2 wide, on the left hand-side of the Tessina stream, with an approximate volume of 1 million m^3 annually. The movement is classified as a rotational slide with a 20-30 m deep failure surface, affecting also the flysch bedrock. Initially it caused the formation of a 15 m high scarp and a 100 m displacement downstream, with consequent disarrangement of all the unstable mass and destruction of drainage systems set up some years earlier. The movements in this area continued with a certain intensity up to June 1992, causing the mobilisation of another 30,000 m^2.

The material from this area, which is intensely fractured and dismembered, was channelled along the river bed where, owing to continuous remoulding and increase of water content it became more and more fluid, thus giving rise to small earth flows converging into the main flow body. After these events, the inhabitants of Funes and Lamosano were evacuated.

SIMULATIONS OF THE 1992 TESSINA LANDSLIDE

Some considerations and constraints that guided us in planning the modelling and simulation of the 1992 Tessina landslide will now be discussed. The dimensions of the landslide and the type of data available led us to choose the parameter edge of the cell 10 metres wide; the resulting CA plane was thus a matrix of 296 ¥ 410 cells.

The simulation doesn't account for the initiation of the landslide, when large blocks move. SCIDDICA is not able to simulate the movements of larger blocks than the cell edge. This initial phase is exhausted quickly in comparison with the duration of the phenomenon, because thereafter such blocks split continuously until reaching complete fluidity.

At the beginning of the simulation, the whole mass involved in the landslide is considered to detach immediately. In reality the cohesion of the detached mass is lost little by little. The simulation may account for this first phase of the landslide when it still has a higher viscosity, before complete fluidity concludes the detachment phase.

A control concerning the altitude is introduced in order to model this first phase: viscosity values are high when mud is above a certain altitude, otherwise the values are lower. The use of these different values accounts for the detachment process: when the mud reaches a certain altitude, the process by which mud becomes fluid can be considered complete. We chose 1050 m as the critical altitude, immediately below the detachment area. The greater viscosity is modelled using larger values of the friction angle. The friction angle for the first phase corresponds to real value of the static friction angle [Pasuto, personal communication 1998]; the dynamic friction angle was not measured but it is, of course, smaller than the static angle. In the second phase, the friction angle must be smaller than the static friction angle. Its value is obtained observing the results of simulations carried out for different values of friction angle.

The "adherence" threshold value was chosen empirically, and takes into account that the thickness of residual mud should not be less than 10 cm. Because of the high degree of saturation of the materials during all the evolutionary stages of the landslide, water content is considered constant in time, an assumption that simplifies the model. The temporal correspondence of a step of the CA was determined after the simulation tests; this can be fixed to 40 minutes.

An example of the best simulations is shown in Figure 1. The values of the parameters are:

Adherence, 1 dm;
friction angle, 25° in the detachment phase and 20° after the detachment phase;
relaxation rate is 2, both in the detachment phase and after the detachment phase;

Simulation step 200 (Figure 5a) shows that the landslide has moved away and the mud flow begins to channel correctly into the river bed. Simulation step 400 (Figure 5b) shows how the mud flow has canalised in the river bed and it is larger than the real event. Probably a smaller cell size would give a better simulation. Simulation step 800 (Figure 5c) shows how the landslide runs correctly along the river bed. Simulation step 1600 (Figure 5d) shows that the mud flow has been divided into two branches near Funes; this area occupied by the landslide coincides closely with the real event.

Simulation step 3200 (Figure 5e) shows the confluence of the two branches. Only a small area between the two branches is not covered by the mud flow – exactly as in the real event. The landslide reaches Lamosano at simulation step 4000 (Figure 5f); the shape of this last part of the landslide path adequately matches the real one. The real event stops at approximately this stage of simulation and has the final shape of the simulated landslide. Continuing the simulation does not lead to further evolution.

Comparison between the real event (Figure 4) and this simulation (Figure 5) shows substantial agreement in the landslide development: the mud path is properly identified and almost all the area covered by mud is included in the simulation. Only a small area – covered by the mud in the real event – does not correspond to the simulation.

FUTURE HAZARD SCENARIOS

The following considerations can be deduced from the study of the Tessina landslide and from the large number of simulations performed in order to obtain a relevant approximation of the 1992 Tessina landslide:

a) The model is well validated in relation to the characteristics of 1992 Tessina landslide and its geo-technical parameters (friction angle and adherence properties), which have been ascertained by means of laboratory tests.
b) Since the bedrock of the landslide area is made up of a flysch formation, the material involved in future landslide events will be the same as in previous slides. Furthermore, rheological conditions, which follow the activation of a new landslide and permit the spreading out of the mud flows, involve almost the same parameters for the simulation.
c) The precise location of the area of detachment is irrelevant for future developments of the landslide, since the mud flows are channelled in the river bed. Simulations of different locations of detachment in the source area give the same results when the volumes involved are equal (of course, different volumes give different results).

These considerations permitted a simple strategy to be developed in order to obtain reliable simulations of future events: first, an accurate and updated morphology of the landslide area must be available; second, an interval of mud volumes must be fixed whose extremes represent the minimum mud quantity needed to obtain a landslide event and for the worst case of detachment. The latter parameters should be fixed by considering previous events. Therefore the simulations must be carried out with volume values compatible with the landslide type; the detachment location may be anywhere in the

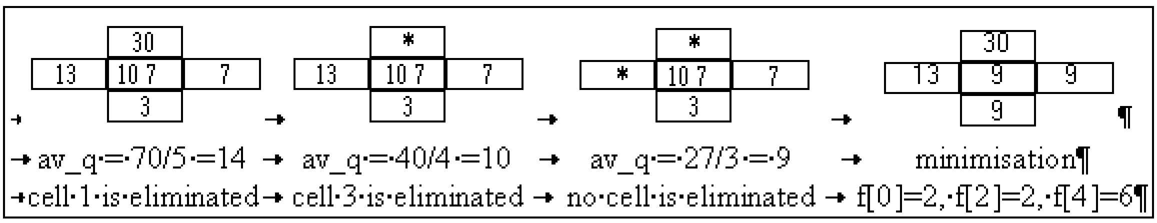

FIGURE 1: Example of minimisation of differences in a two-dimensional CA.

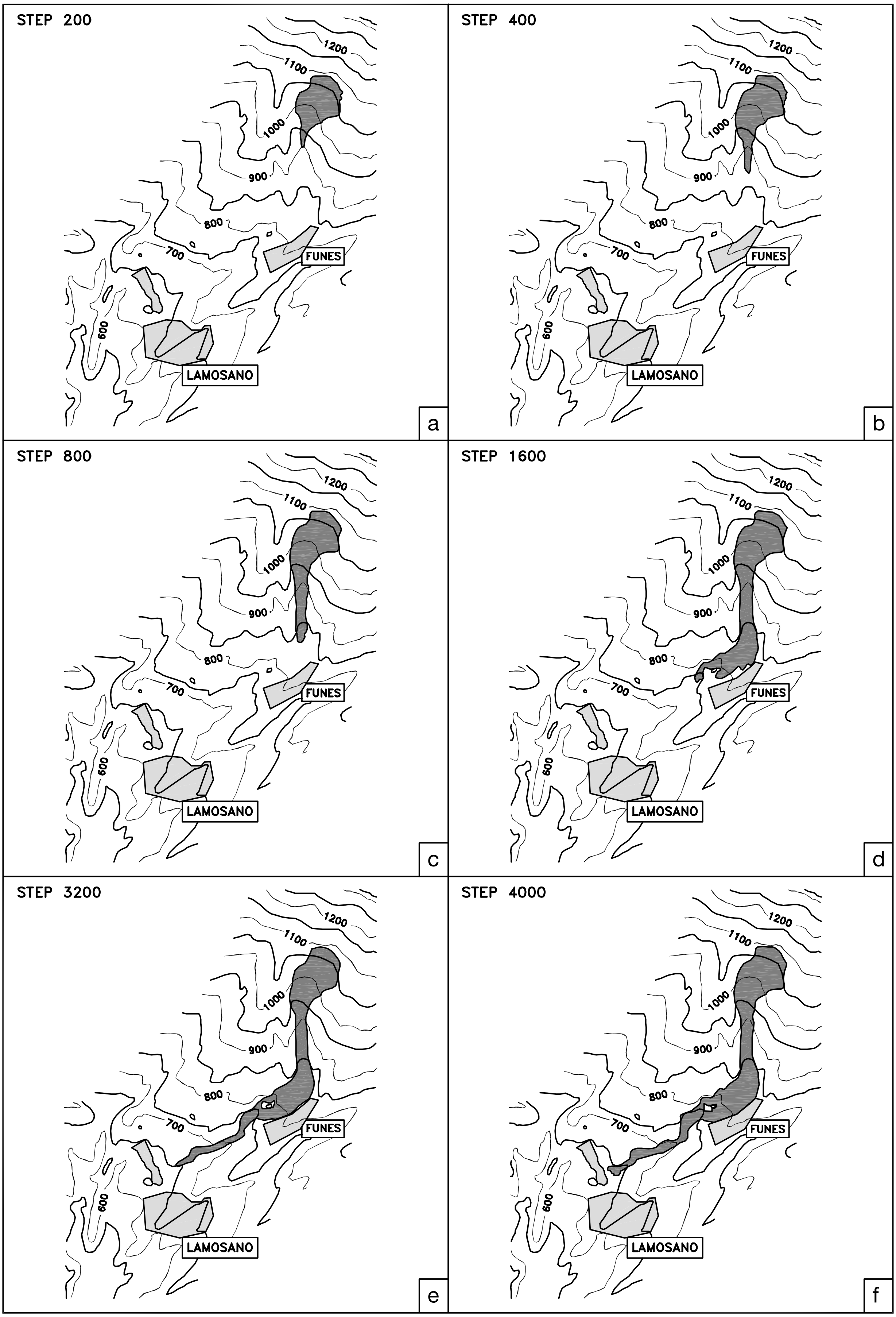

FIGURE 5: Simulation of the 1992 event obtained by the Cellular Automata Model.

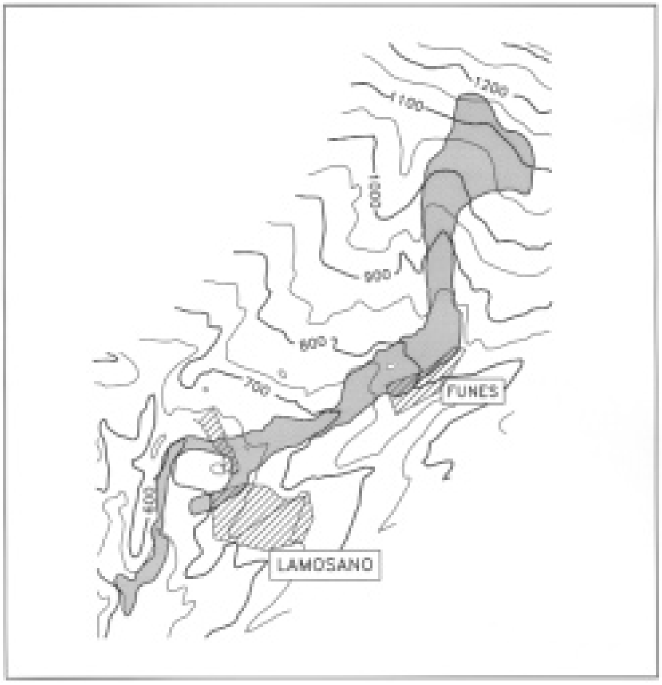

FIGURE 6: Prediction of a future scenario due to remobilization of about 1 million m3 of material.

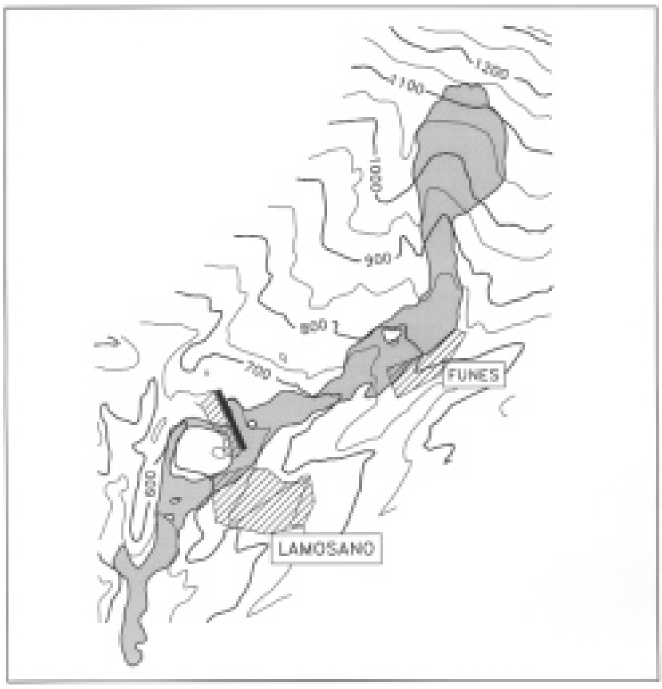

FIGURE 7: Effect of containment wall in the scenario shown in Figure 6.

area of detachment.

On the basis of these remarks, two different situations were simulated. One of them involved a volume of about 1 million m^3, which was considered more than probable from experience with previous movements, and which buried the morphological features resulting from the September 1998 events. For this purpose, a detailed topographic survey was carried out in order to update old topographic maps.

The result of the simulation shown in Figure 6 pinpoints the considerable involvement of the Funes and Lamosano villages in the flow which, in the sector immediately downstream of Funes, shows a tendency to overflow towards the adjacent valley. In the second simulation (Figure 7), a containment wall was inserted downhill of Lamosano. Following the 1992 events this structure was built for the defence of the hamlet Tarcogna. It can be clearly seen that this structure is not effective protection for the inhabited centres and, as in the case of Lamosano, it may even make the situation worse. Most of the flow material should pass through the main collecting canal, which passes through the village centre.

On the basis of the results obtained, the risk for these villages has been identified as high in cases of future reactivation of the slope movement. This will inevitably lead to a complete reconsideration of the civil defence procedures set out so far. As a consequence, heavy restrictions on land use will be considered and they may even include partial evacuation and transfer of Funes and Lamosano villages.

CONCLUSIONS

Results of first simulations using SCIDDICA are promising. With this model the landslide path was reproduced, despite difficulties in simulating the initial movement of the slide (rotational slide) by using CA. Nevertheless, accurate simulation of the initial part does not influence the simulation of the development of the general phenomenon.

Moreover the close correspondence between the real and the simulated event should be pointed out. A comparison between Figures 4 and 5 shows substantial agreement in landslide development, the mud path is clearly marked and almost all the area covered by the mud is included in this simulation.

This good result permitted us to simulate a possible future event, one of a magnitude comparable to the previous slide, using parameters found for the simulation, since the physical characteristics of the landslide do not change significantly in time. The results obtained are given in Figures 6 and 7 show a situation of real risk affecting the hamlets involved in the landslide and underline the need to take adequate countermeasures.

The experience acquired from the Tessina landslide was useful for better identification and definition of the potential applications of this procedure in order to forecast areas potentially involved in low-viscous landslides, such as debris flow and mud flow. It is therefore acknowledged that this kind of simulation may be very useful for civil defence purposes since it allows threatened areas, which should be protected or evacuated, to be identified. In particular, Cellular Automata may be successfully used in order to:

a) forecast landslides in areas for a variety of initial detachment zones, in order to undertake correct risk zoning;
b) follow the progress of an event and predict its evolution;
c) verify the possible effects on real or simulated flows of man's intervention in stream diversion. Introduction of data, which represent alterations to original conditions or to present ones (*eg*, the construction of a canal or an embankment), is possible during the simulation.

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RÉSUMÉ

"Cellular Automata" sont des outils puissants pour modeler des systèmes naturels et artificiels, qui peuvent être décrits en termes d'interactions locales de leurs parties constituantes. Certains types de glissements de terrain, tels que débris/coulées de boues, correspondent à ces exigences. Le glissement de terrain de Tessina en 1992 a des caractéristiques (coulées de boues lentes) qui le rend approprié pour une modélisation au moyen de "cellular automata", à l'exception de la phase initiale du détachement, qui est causé par un mouvement de rotation qui n'a pas d'effet sur le cours de la coulée de boue. Cet article présente l'approche de "cellular automata" pour la modélisation des coulées de boues/débris lents, les résultats de la simulation du glissement de terrain de Tessina en 1992 et des scénarios de risques futurs sur les volumes de masses qui pourraient être mobilisés dans le futur. Ils ont été obtenus en adaptant le Modèle des "Cellular Automata" appelé SCIDDICA, qui a été validé pour des glissements de terrain très rapides. SCIDDICA a été appliqué en modifiant le modèle général aux particularités du glissement de terrain de Tessina. Les simulations obtenues par ce modèle initial étaient satisfaisantes pour prédire la surface couverte de boue. La calibration du modèle, qui a été obtenue à partir d'une simulation de l'événement de 1992, a été utilisée pour des prévisions d'expansion de coulée au cours de possibles réactivations futures. Pour cette raison deux simulations concernant un détachement d'environ 1 million de m^3 de matériel a été testé. Dans l'un des cas, la présence d'un mur de soutènement construit en 1992 pour la protection du hameau de Tarcogna a été inclus. Les résultats obtenus ont identifié les conditions de haut risque affectant les villages de Funes et Lamosano et montré que cette approche de "cellular automata" peut avoir une grande portée d'applications pour différents types de coulées de boues/débris.

RESUMEN

Los autómatas celulares (Cellular Automata) son una poderosa herramienta para la modelización de sistemas naturales y artificiales, que se pueden describir considerando las interacciones locales de sus partes constituyentes. Algunos tipos de corrimientos, como son las corrientes de rocalla o lodo, satisfacen estos requisitos. El corrimiento de tierras de Tessina de 1992 tiene unas características (corrientes lentas de lodos) que lo hacen apropiado para la modelización por medio de los Cellular Automata, excepto en la fase inicial del desprendimiento, que está provocada por un movimiento de rotación que no tiene efecto en la trayectoria de la corriente de lodo. Este artículo presenta el método de Cellular Automata para la modelización de corrientes lentas de lodo y rocalla, los resultados de la simulación del corrimiento de tierras de Tessina de 1992 y el pronóstico de futuros riesgos teniendo en cuenta los volúmenes de masas que se podrían movilizar en el futuro. Estos se obtuvieron adaptando el modelo Cellular Automata conocido como SCIDDICA, que ha sido validado para corrimientos de tierra muy rápidos. Se aplicó SCIDDICA modificando el modelo general con respecto a las peculiaridades del corrimiento de tierras de Tessina. Las simulaciones obtenidas con este modelo inicial fueron satisfactorias para predecir la superficie cubierta por el lodo. La calibración del modelo, que se obtuvo de la simulación del suceso de 1992, se utilizó para pronosticar la expansión de la corriente durante una posible reactivación en el futuro. Para este fin se estudiaron dos simulaciones sobre el desplome de aproximadamente 1 millón de m^3 de material. En una de ellas, se introdujo la presencia de un muro de contención construido en 1992 para la protección de la pequeña aldea de Tarcogna. Los resultados obtenidos identificaron las condiciones de alto riesgo que afectaban a los pueblos de Funes y Lamosano y demostraron que este método de Cellular Automata puede tener una amplia gama de aplicaciones para diferentes tipos de corrientes de lodos y rocalla.