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The CA-model FLOW-S* for flow-type landslides: an introductory account

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Abstract: Several studies have recently been carried out, aiming at characterising flow-type landslides and suggesting approaches for planning either active or passive countermeasures. The physics of flow-type landslides includes various complexities of multiphase materials characterised by heterogeneities in time and space. In cases of rapid or extremely rapid phenomena, the prediction of flow movement, and of the likely inundated areas, is usually a severe task, and is therefore important to develop reliable strategies for hazard assessment.

Modelling and simulation techniques can be a precious tool for risk assessment and mitigation. Different conceptual approaches, ranging from laboratory experiments to numerical schemes, have recently been proposed. Among them, some are specifically aimed at evaluating the susceptibility or the hazard posed by debris flows.

A family of models for simulating flow-type landslides has recently been developed within the frame of a cooperation project between CNR-IRPI and University of Calabria. Such models belong to the class of Cellular Automata (CA) for Macroscopic Fluids. The early releases of the family were quite empirical and simplified, and ignored most of the physical characteristics of the type of landslides under consideration. In the recent releases, the models resulted to be quite robust, did not show problems of numerical instability, allowing to fully incorporate even very-dense DEMs.

FLOW-S* is the most recent version of the mentioned CA-family, by far the most physically-constrained. It has been developed by referring to the well-known "equivalent-fluid" and "geotechnical" modelling approaches, by properly transposing their fundamentals into the discrete space-time framework of the macroscopic CA method. In the model, the material moves from a given cell to one of the neighbourhood driven by the gravitational acceleration along the local slope, and affected by dissipative and pressure terms. Momentum conservation is guaranteed, as well as a proper management of collisions; mass conservation depends on processes of entrainment, which may occur along the flow path. Energy conservation depends on selected dissipative processes. Finally, model parameters reflect the CA approach, but are also related to the characteristics of the material involved, and to the type and rheology of the phenomenon.

Model performances have been tested against several ideal cases, and by also considering real events recently occurred in Southern Italy. Further tests are being performed by considering data from flume experiments, by employing different types of water-debris mixtures.

First results of sensitivity analyses and calibration/validation experiments are encouraging and underline the potential of the model for susceptibility mapping and for hazard mitigation purposes. An introductory account on the employed approach is presented in this paper, with examples of analyses performed by considering an ideal case (a roughly bi-planar surface), and a real event (the Vallone Favagreca debris flow) triggered on 12 May 2001 near Scilla, in Calabria - Southern Italy.

Keywords: *CA-modelling, flow-type landslides, rapid flows, susceptibility*

1. INTRODUCTION

Considerable loss of human life and property has been caused by flow–type landslides in many regions of the world in historic time. Amid flow-type landslides (e.g. earth flows, debris flows and avalanches), the fast–moving events (generically named “rapid flows” herein, for the sake of brevity) are among the most destructive and, when occurring under natural conditions, are also the most difficult to prevent (Hungr, 2004). In the initiation zones, a mantle of heterogeneous regolith commonly covers, in a precarious state of equilibrium, the slopes cut in bedrock. Debris mobilization generally requires a direct hydrologic trigger; secondary climatic factors (such as antecedent rainfall, or snowmelt) may influence whether rapid flows will be actually triggered during an earthquake, a volcanic event, or an intense storm (Wieczorek and Glade, 2005). Hungr et al. (2001) distinguished the following main types: “debris avalanches”, which initiate on steep slopes, and strongly accelerate thanks to relief energy; “debris flows”, which occupy established channels and are characterized by entrainment of saturated debris from the path, surging, internal sorting and mixing with surface water; “flow slides”, which involve *in situ* liquefaction of the source material, where material prone to spontaneous or earthquake-induced liquefaction is available. rapid flows commonly originate from: a) progressive erosion, and consequent increase of the solid concentration in subaerial flows, as a consequence of runoff during severe storms, often in areas recently affected by wildfires (e.g. Cannon et al., 2001); b) soil slips which fluidify and transform into flows; c) collapse of natural or man–made dams; d) liquefaction due to sudden loading of regolith by oncoming material from upslope, spontaneous liquefaction, or dynamic solicitations.

According to Giraud (2005), a comprehensive evaluation of the hazard posed by rapid flows requires an understanding of the processes which govern sediment supply and bulking, flow volume and frequency, and deposition. In such a context, the assessment of the runout plays a fundamental role (Hungr, 1995), in terms of areas potentially affected by the propagation of an initial failure, maximum distance reached, flow velocity and thickness, depth of erosion of the regolith, flow behaviour in bends and at obstacles along the path. At such purpose, modelling and simulation techniques may represent a valuable tool (e.g. Ellen et al., 1993; O’Brien et al., 1993; Iverson et al., 1998; Laigle and Marchi, 2000; Iovine et al., 2003a, b).

Rapid flows are constituted of complex multiphase materials, characterized by heterogeneities in time and space (e.g. Iverson, 1997). In the past decades, several attempts of evaluation of the areas threatened by the development of a given phenomenon were performed through different modelling approaches (for an extensive list of references, cf. D’Ambrosio et al., 2007). At least for preliminary purposes, a proper but simplified approach seems appropriate. Following this trail, a family of Cellular–Automata (CA) models was developed for simulating rapid flows after the May 1998 disaster in Campania (Southern Italy). The former versions (cf. Iovine et al., 2003a, and references therein) ignored - or treated in a very-simplified way - the process of regolith erosion and the effects of inertia, which may instead become significant in case of flow on steep slopes. The CA-model FLOW-S*, derived from the same family, is able to simulate cases of either rapid or extremely rapid flows originated by fluidification of former sliding material (case b, above), besides the entraining of regolith along the path due to sudden loading (case d). Events of dam collapse (case c), progressive erosion of regolith (case a), and branching/re–joining of the flow masses, can also be accounted for. In FLOW-S*, dissipative effects are modelled in terms of velocity–dependent mechanisms. Peculiar characteristics of extremely–rapid flows, and the effects of mass collisions, are correctly managed, by guaranteeing mass conservation; in case of no dissipation, conservation of energy and of momentum are also assured. Effects of internal pressure in the flowing body are explicitly handled.

Preliminary calibration and sensitivity analyses were carried out by means of sequential Genetic Algorithms, and by considering i) different ideal case studies, and ii) selected cases occurred at Pizzo d’Alvano (Campania, Southern Italy) during the May 1998 disaster. Further tests and validation experiments were performed against similar study cases, occurred at Pizzo d’Alvano during the same 1998 event, in the San Martino Valle Caudina–Cervinara area (Campania) in December 1999, and in the Bagnara-Scilla area (Calabria, Southern Italy) in May 2001 and March 2005. First results confirmed the reliability of the model in reproducing the considered types of phenomena. Further tests will be carried out for evaluating the behaviour of the model in different geological settings and against a significant number of real and laboratory cases.

An introductory account on the employed approach is presented in the following sections, with examples of analyses performed on an ideal case study (bi-planar surface) and on a real event, occurred on 12 May 2001 in the Vallone Favagreca (Bonavina et al., 2005), near the village of Favazzina-Scilla in Calabria (Figure 1).

2. THE MODELLING APPROACH

A simplified semi–empirical modelling approach was assumed in the present study, inspired from the equivalent fluid (Hungr, 1995) and the geotechnical model (Sassa, 1988). The moving mass is in fact replaced with a column of debris, whose bulk properties allow to approximate the behaviour of the real cases. The original sliding material in the source "immediately" (i.e. in one single step) transforms into a flowing mass, thus originating the flow (cf. cases b and c, above). The computation of the flows among the cells is based on the "minimization algorithm of the differences" (Di Gregorio and Serra, 1999) and on the rules cited below. For the sake of brevity, only the main differences which distinguish FLOW-S* from the previous releases of the family are mentioned.

The model can be formally defined by the quintuple: FLOW-S* = < R, X, Q, P, σ >, where R is the cellular space, X identifies the geometrical pattern of the neighbourhood, $Q=Q_z\times Q_h\times Q_r\times Q_o^7\times Q_E\times Q_{px}\times Q_{py}$ is the finite set of states of the cell, defined as the Cartesian product of the substates (cf. Table 1), $P = \{p_c, p_t, p_\varphi, p_\delta, p_{\gamma f}, p_{Pbed}, p_{kf}, p_d, p_{vc}, p_{mt}, p_{pef}, p_{ltt}\}$ is the set of parameters (cf. Table 2), σ: $Q^7\rightarrow Q$ is the deterministic transition function, made of a set of three elementary processes which simultaneously occur within each cell of the cellular space at each step of computation. In order of application, they are: σ_1: regolith erosion, σ_2: computation of the "minimizing" outflows (i.e. of the flows from the central cell toward the neighbouring ones, able to minimise existing differences in the considered amounts), σ_3: mass, energy and momentum update.

The landslide mass is represented in terms of an equivalent fluid, by means of a number of columns of debris, each located within a given cell and characterized by various thickness and energetic properties. Such volumes are let free to deform as a consequence of a net driving force (F), which can be schematically assumed as the algebraic sum of the tangential component of the weight (W), the basal resisting force (T), and the tangential internal pressure resultant (P). In other terms: $F = W + P - T$.

Following Rickenmann and Koch (1997),

$$W = \gamma \cdot V \cdot \sin\alpha \tag{1}$$

$$P = -k^{a/p} \cdot \gamma \cdot V \cdot \frac{\Delta h}{\Delta s} \cdot \cos\alpha \tag{2}$$

in which $k^{a/p}$ is the earth pressure coefficient (see below), γ is the bulk unit weight of the flowing mass, V is the volume of the landslide mass in the cell, Δh is the difference of landslide thickness between the central and the neighbouring cell, α is the basal slope angle, $\Delta s = 2p_c / \cos\alpha$ is the displacement of the debris, and T is the basal flow–resistance term, depending on the rheology of the material (which can be specified by employing suitable dissipative mechanisms). In FLOW-S*, the earth pressure coefficient, $k^{a/p}$, is defined according to the expressions proposed by Savage and Hutter (1989), derived from the classical Rankine earth–pressure theory:

$$k^{a/p} = 2\frac{1 \mp \left[1-\cos^2\varphi \cdot (1+\tan^2\delta)\right]^{1/2}}{\cos^2\varphi} - 1 \tag{3}$$

in which φ is the internal friction angle of the landslide material, and δ is the friction angle of the same material on the channel bed. The double sign "$\mp$" in the expression for $k^{a/p}$ depends on either extending ("active") or compressing ("passive") conditions of the flow, for which "–" or "+" respectively apply:

$$k^{a/p} = \begin{cases} k^a \;\; if\, \dfrac{\Delta v}{\Delta s} \geq 0 \\ k^p \;\; if\, \dfrac{\Delta v}{\Delta s} < 0 \end{cases} \tag{4}$$

For simulation purposes, besides assigning proper values to the parameters, the model must be initialized through the following set of input matrices: the pre–event topography, the landslide source, and the thickness of erodable regolith. All the remaining sub-states are initialised to zero (including the initial velocity of the soil slip). For calibration purposes, additional matrices can be used – such as the area affected by the real event, the thickness of the deposit, the depth of erosion along the path. Triggering of secondary sources can also be simulated, by specifying their location and extent: the activation is managed either by specifying a pre-fixed starting step, or by utilising "transepts" (one for each secondary source). In this latter case, a threshold (p_{ltt}) for the thickness of the flow crossing each transept must be specified, and the activation of the secondary slips is handled accordingly. Finally, three stopping criteria can be selected: i) maximum number of steps, ii) minimum thickness of outflows, and iii) maximum velocity of outflows. The first two criteria must be explicitly decided at the beginning of each simulation, while the last one is a function of the cell size and of the duration of the time step (cf. "temporal error", below).

Table 1 – List of the sub-states of FLOW-S*.

substate	*definition*
Q_z	elevation of the cell [m a.s.l.]
Q_h	thickness of landslide [m]
Q_r	depth of erodable regolith [m]
Q_o^7	outflows of landslide [m]
Q_E	mechanical energy of the landslide [J]
Q_{px}, Q_{py}	components of the momentum of the landslide along the directions *x* and *y*, respectively [kg m/s]

Figure 1. Rapid flow occurred in the vicinity of Scilla (Calabria) at Vallone Favagreca on 12 May 2001 (*photo: courtesy of A. Pellegrino*).

3. THE ELEMENTARY PROCESSES

Let us consider a "column" of mass *m* (with constant density ρ), base *A* and thickness *h* at elevation *z*, which moves at velocity $\vec{v}$. The process of entrainment along the path (σ_1) is simulated by considering the parameters p_{et} and p_{pef}, in the same way as in Iovine et al. (2005): when the energy (q_E) overcomes a prefixed threshold (p_{et}), and the kinetic head (h_k) is greater than zero, the erosion of the regolith can occur. Depth of erosion depends on debris energy (q_E) and on "progressive erosion" (p_{pef}). Due to their empirical character, the values of the parameters p_{et} and p_{pef} have to be chosen through back–analysis. At each step, the depth of erosion, expressed as elevation variation (Δz), is given by:

$$\Delta z = \begin{cases} 0 & if\ q_E \le p_{et} \vee h_k = 0 \\ \min\left(q_r, q_E \cdot p_{pef}\right) & if\ q_E > p_{et} \wedge h_k > 0 \end{cases} \tag{5}$$

Table 2 – List of the parameters of FLOW-S*. In the last two columns, the values used for the reference ideal case, and for the 2001-real event at Favagreca-Scilla are also listed, respectively (cf. Figures 1 and 2).

parameter	*definition*	*value*	*value*
p_c	apothem of the cell [m]	1.25	5.0
p_t	time step, i.e. temporal correspondence of a single step [s]	0.1	0.5
p_φ	internal friction angle of the landslide material [°]	35	35
p_δ	friction angle of the landslide material on the channel bed [°]	20	20
$p_{\gamma f}$	saturated unit weight of the debris [kN/m^3]	20	24
p_{Pbed}	factor of basal interstitial pressure [dimensionless]	0.5	0.6
p_{kf}	shear strength of the debris [kPa]	0.7	2.4
$p_d=\{p_{dP}, p_{dQ}, p_{dR}\}$	parameters ruling the energy loss based on flow velocity [dimensionless]	0.16, 0.005, 1.0	0.9, 0.4, 0.0
$p_{vc}=\{p_{vcP}, p_{vcQ}, p_{vcR}\}$	threshold of velocity for applying different types of energy loss [m/s]	1.0, 50.0, 100.0	1.0, 50.0, 100.0
p_{mt}	mobilization threshold for regolith erosion [m/s]	0.1	1.0
p_{pef}	factor of progressive erosion [dimensionless]	1.0	0.5
p_{ltt}	threshold of landslide thickness (in transepts) for triggering secondary sources [m]	0.1	1.0

The computation of the outflows (σ_2) is carried out by means of a two–step procedure: "ideal" minimizing outflows are first evaluated by applying the mentioned minimization algorithm of the differences; "actual" outflows can then be computed from the ideal ones at each step, by considering the duration of the time step, and the effects of dissipative mechanisms and of internal pressure. Ideal outflows are computed by applying an approach already discussed in Iovine et al. (2005): the minimization algorithm is applied to a "modified" morphological context, in which the alteration of the local topography is the more important the higher the kinetic properties of the moving mass. Actual outflows, $f(0,i)$ (i=1,2,...,6) – i.e. the debris outflows which actually move among the cells during the considered step of computation – are then derived from the ideal ones by taking into account the duration of the CA time step: depending on p_t, the ideal equilibrium condition pursued by the minimization algorithm can in fact be achieved in more than one single step of computation. Neglecting both dissipative and internal pressure effects, the aliquot $f(0,i)$ of the ideal minimizing outflow, $q_o(0,i)$, that can reach the i^{th} neighbouring cell is:

$$f(0,i) = q_o(0,i)\frac{v(0,i)p_t}{2p_c/\cos\beta} = q_o(0,i)\frac{\Delta s}{\Delta s_{\max}} \qquad (6)$$

where: $v(0,i)$ is the velocity associated to the i^{th} minimizing outflow, which moves along an inclined direction with slope angle β=arctan($\Delta\chi/2p_c$); $\Delta s=v(0,i)\cdot p_t$ is the displacement in the time step; $\Delta s_{max}= 2p_c / \cos\beta$ is the maximum displacement permitted within a single step. If $\Delta s>\Delta s_{max}$ in one or more cells during a simulation, a "temporal error" occurs: the simulation stops, and the CA clock, p_t, must be properly reduced, before a new experiment can be launched. In order to compute the amount $f(0,i)$, the velocity $v(0,i)$ of the minimizing outflow must also be evaluated. In general terms, it can in fact be written:

$$v_a = v_{kinematical} + v_{pressure} - v_{dissipation} \qquad (7)$$

Accordingly, an approximation in the computation of $f(0,i)$ was introduced, by considering $v(0,i)$ as the average between the starting velocity (v_s) and the arrival velocity (v_a). Aiming at dealing with the effects of tangential internal pressure (P), compressive or extensive conditions must be determined for the flowing mass, and the value of the earth pressure coefficient ($k^{a/p}$) must be computed accordingly. Effects of dissipation are taken into account in order to determine the value for actual velocity. Similarly to the approach adopted by D'Ambrosio et al. (2007), in the case of a mass moving along a slope, the energy loss due to frictional dissipation can ideally be modelled by considering the following velocity–dependent types of mechanism (cf. Erismann and Abele, 2001), which act at the base of the mass: P ("Proportional"), Q ("Quadratic"), and R ("Reverse"). In particular, type P implies a linear relation between resistance and velocity (e.g. motion of a laminar layer of viscous fluid), while type Q determines a proportional relationship between resistance and the square of velocity (e.g. motion of a turbulent layer of watery fluid). Finally, type R allows for modelling the situation of resistance decreasing with velocity, which is sometimes observed when velocity exceeds a given threshold. The three mechanisms can be applied alternatively, by properly selecting velocity ranges of application (cf. p_{vc} in Table 2). Once $f(0,i)$ (i=1,2,...,6) are known, the debris content, energy and momentum can finally be updated (σ_3).

4. DISCUSSION

Preliminary tests confirmed the suitability of the model for simulating flow-type landslides; accordingly, susceptibility evaluations may be performed by adopting the procedures already tested with previous releases (cf. Iovine, 2008). Simulations were evaluated in a quantitative way, by computing a fitness indicator defined as $e_1 = \sqrt{(R \cap S)/(R \cup S)}$ which compares the affected areas of the real (R) and simulated (S) events. It may range between 0 and 1 (it is 1 in case of perfect simulation, 0 for an absolute failure). Further experiments are still being performed, by employing a greater set of real cases, in order to thoroughly verify the performances of the model in different geological settings.

Examples of simulations of an ideal case, with the results of three parametric analyses, and of a real event are shown in Figure 2. Experiments were carried out by considering an ideal reference case, related to following simple geometrical configuration: a roughly bi-planar surface, with a concave-upward profile in longitudinal section and plane in cross section, and with a uniform thickness (2.5 m) of erodable material. The model parameters of the reference case were selected by considering previous tests, as well as the need of a suitable final shape and depth of erosion; in this way, the ability of the model could be properly verified. The parameters proved to differently affect the results of simulation: in some cases, their role appears to be quite marginal, or linear; in others, a complex behaviour or appreciable changes of fitness resulted even for small variations of the parameter. Other tests are being performed against different ideal cases, and by considering either real events or laboratory cases. In Figure 2, an example of simulation of the 2001 Favagreca rapid flow is also shown, together with an aerial view of the area affected by the May 2001 and March 2005 events. More details on adopted parameters are given in Table 1; for the fitness results, see the caption of Figure 2.

With respect to the previous versions of the family, FLOW-S* represents a significant step forward in terms of dynamic modelling of rapid flows: the physical description of the phenomenon is in fact refined, although remaining within a semi–empirical macroscopic CA approach. Indeed, whilst constrained within a discrete space–time framework, the model reflects classical modelling schemes: movement of debris masses is driven by gravitational acceleration (i.e. the tangential component of weight), which may be contrasted by a basal resisting force (depending on rheology), and by the effects of internal pressure (reflecting rigidity of the flowing mass). The moving material, which may actually be heterogeneous and complex, is approximated by means of an “equivalent fluid”, whose bulk properties are macroscopically similar to the real case. Model parameters are mostly related to the constitutive properties of the assumed equivalent fluid; they cannot be directly measured in laboratory tests, but must be determined through calibration (i.e. back analyses of real cases). In addition to an improved treatment of velocity, effects of collisions are better managed, and conservation of energy and momentum is guaranteed. Effects of internal pressure and dissipation are explicitly treated, by following an approach similar to the one discussed in Rickenmann and Koch (1997).

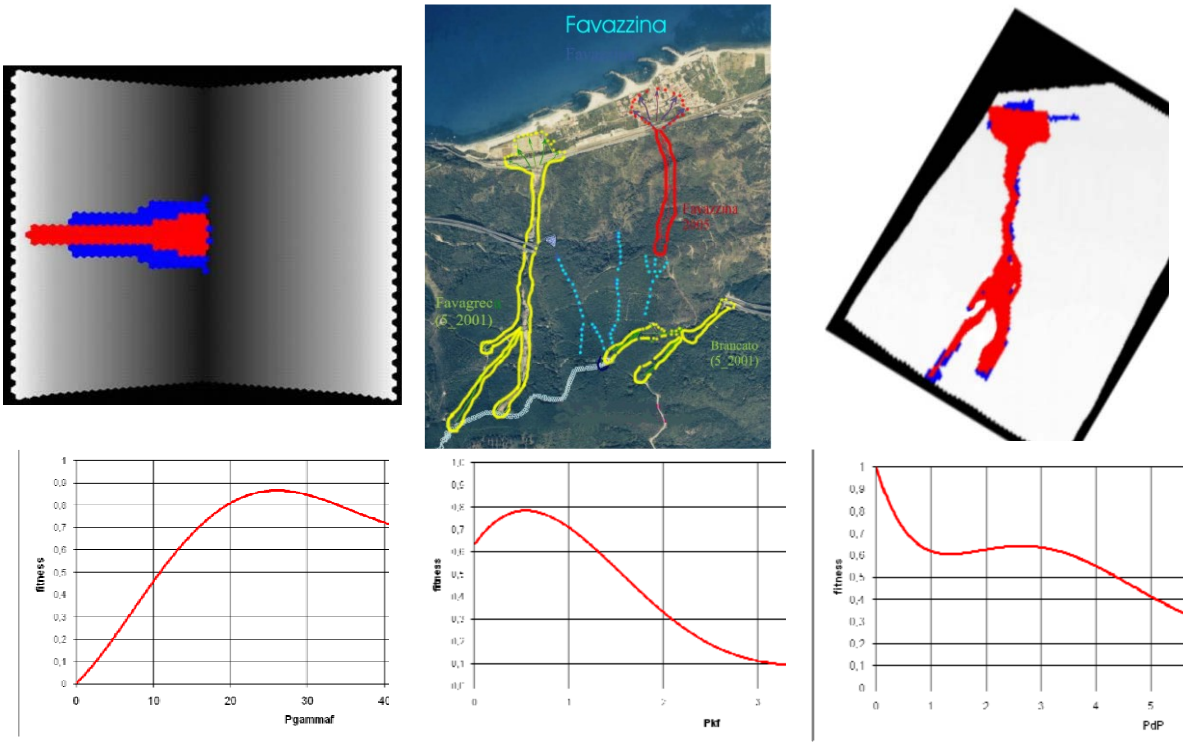

Figure 2. Top-left: The ideal reference case (in blue) employed for the parametric analyses, obtained on a roughly bi-planar surface (final step=4836, e_1=0,715), covered by a simulated case (is in red). Matrices are made of 51 rows x 51 columns, with elevations symmetrically ranging from 100 to 70 m a.s.l. (steps of 2 m between 100 and 90, and of 1 m between 90 and 70 m a.s.l.). Top-middle: rapid flows occurred in the vicinity of Scilla (Calabria) at Vallone Favagreca (on left, in yellow) and at Brancato (on right, in yellow) on 12 May 2001, and at Favazzina on 31 March 2005 (in red); paths of severe erosion are dotted in light blue (after Mercuri and Pellegrino, unpublished report, mod.). Top-right: simulation of the Favagreca rapid flows (final step=15000, e_1=0.739). On bottom, from left to right: results of parametric analyses for $p_{\gamma f}$, p_{kf}, and p_{dP}, respectively, carried out by considering the ideal case.

If compared with lumped mass models, FLOW-S* allows for predicting the propagation of the flow front, besides other details on the phenomenon and the overall affected area (e.g. mass distribution and flow velocity, thickness of deposit, depth of erosion). Yet, differently from most continuum mechanics models, it allows for the selection of a variety of material rheologies, by providing a set of velocity–dependent dissipative mechanisms for the simulation of even highly-complex behaviours. The propagation of the flow onto complex topography or open slopes is also accounted for. Erosion of the regolith along the flow–path (according to the energy of the flowing mass) as well as events of branching or re–joining of the flow masses can also be simulated, and peculiar characteristics of rapid flows can therefore be taken into account.

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