imProved Accessibility: Reliability and security of Alpine transport infrastructure related to mountainous hazards in a changing climate

Introduction to the operative tool and debris flow models

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Table of contents

U0 – Introduction

The operative tool, OT, for a complete debris flow process simulation is a user-friendly Gis-based graphic interface which groups a few models simulating debris flow triggering, routing, deposition and impact against obstacles. Each phase of the debris flow dynamics (initiation, routing, deposition, impact), in fact, needs a separated modeling approach. The graphical interface will be designed to allow the use of the single models or a free combination of them according to the needs of the user.

The considered models are the triggering model, the routing model, the inundated areas delineation model and the debris flow impact model. In the following table a synthesis and a short presentation of the models.

Table 1: The models that constitute the operative tool.

Debris flow triggering model (PP5)	hydrological model coupled with an inception sediment transport relationship at high slopes
Debris flow routing model (PP7):	cellular automata model
Delineation of debris flow inundated areas model (PTA)	empirical-statistical model
Debris flow impact model (PTA):	model of the forces exerted on a structure when debris flow impacts it
Gis-based graphic interface (PTA)	Gis-based interface which integrates all the models

In the figure below a scheme of the OT with the links between the models.

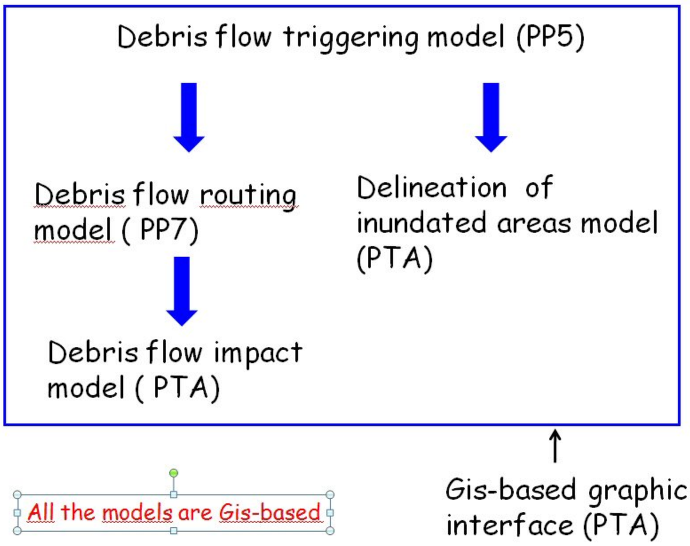

Figure 1: Scheme of the operative tool.

The triggering model is the first model to be used and its output is the input of the routing model and the delineation of inundated areas model. The output of the routing model is the input of the debris flow impact model. The following the description of the single models.

U1 – Triggering model

A number of recent studies (Griffiths et al. 1997; Tognacca et al, 2000; Gregoretti, 2000; Berti and Simoni, 2005; Griffiths et al. 2004; Godt and Coe, 2007; Coe et al, 2008a, 2008b; Gregoretti and Dalla Fontana, 2008; Tecca and Genevois, 2009), relates the triggering of debris flow on either incised channels or on a hillslope, to the erosion power of the water stream flowing over the sediment bed. The triggering model is based on the comparison between the surface runoff simulated by a kinematic distributed model and the critical value for debris flow initiation computed by an empirical law. When the surface runoff discharge in the channel is larger than the critical value, debris flow occurs.

U2 – Hydrological model

Runoff is simulated by a physically based and distributed hydrological model (Gregoretti and Dalla Fontana, 2008) that is derived from the KLEM model (Kinematic Local Excess Model) proposed by Cazorzi (2002) and used for computing hydrograph discharges (Borga et al., 2007; Norbiato et al. 2009; Sangati e Borga, 2009; Sangati et al, 2009). This model is similar to the one proposed by Moretti and Montanari (2003) to estimate the peak flow in ungauged catchments. Brath et al. (2001) showed the efficiency and strength of this type of model when applied to catchments with limited data availability, especially in comparison with lumped approaches. The basin is divided in square cells and for each of these the effective rainfall or runoff production is computed by the Curve Number (CN) method of the Soil Conservation Service. The runoff is then propagated to the basin outlet (the triggering site) along the flow path and the channel network derived from the digital elevation model (DEM) on the basis of the topographic gradient and in the case of channel network also by the contributing area (figure 2). Different propagation velocities are assigned to the channel network and to the flow paths along hillslopes. The velocities along the flow paths are varied, depending on the soil characteristics (e.g., runoff velocity on rocky soil is larger than that on a scree). The hydrograph at the outlet is obtained adding the single cell runoff productions (discharge pulses) that reach the outlet in the same computation time interval.
This type of model is suitable for head-water basin because the runoff production computed by the CN method is reliable, the propagation of runoff to the outlet is well represented by considering parameters (assigned propagation velocities) with clear physical meaning and values in relatively well defined ranges. It is stressed that the model could not be validated in absence of rainfall because of the lack of runoff and during precipitation because of the danger of falling rocks and the difficulty of access to the head-water basins that make not possible the measurement of discharges.

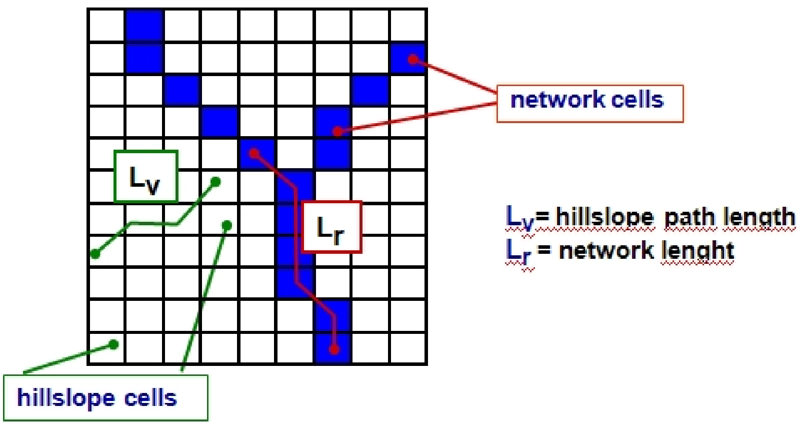

Figure 2. Sketch of the cells flow path and channel network.

U3 – Water sediment hydrograph

The comparison of runoff production and sedimentological characteristics of debris deposits in the triggering sites proposed by Gregoretti and Dalla Fontana (2008) suggests that incipient debris flow formation is likely expected when the peak runoff discharge is larger than the discharge determining the incipient motion of material composing the sediment deposits (differences between simulated peak discharges times and occurrence times in the order of few minutes in 20 debris flow events). In particular, data from experiments carried out on laboratory flumes at high slopes were used by Gregoretti and Dalla Fontana (2008) to provide an empirical law yielding the estimate of the surface runoff necessary to trigger a debris flow, given the slope and the composition of the sediment bed. This empirical law was positively tested by predicting the triggering of debris flow for the simulated peak water discharges of twenty occurred debris flows.
The sum of the runoff production at the onset of debris flow and the sediment deposit volume in the triggering site will be used to determine the water-sediment hydrograph needed as input by routing models.

U4 – Inundated area delineation model

The inundated area delineation model, DFLOWZ, (Berti and Simoni, 2007) is an empirical-statistical model designed to delineate the inundated areas on a fan by a debris flow during the deposition phase. This model is based on the observation that cross sectional flow area, the planimetric area and deposit thickness of a debris flow are linearly correlated to the debris flow volume on a logarithmic scale, with high statistical significance (figure 3).
Assuming a constant cross sectional area, through the DEM, it is possible to compute the inundated area both for the cases of confined and unconfined flow (figure 4). This method allowed satisfactory results for debris flow occurred in the Italian Alps for which the coefficients of the linear correlation in logarithm scale between the different variable can be considered constant with committed errors within the 0.9 level of confidence.

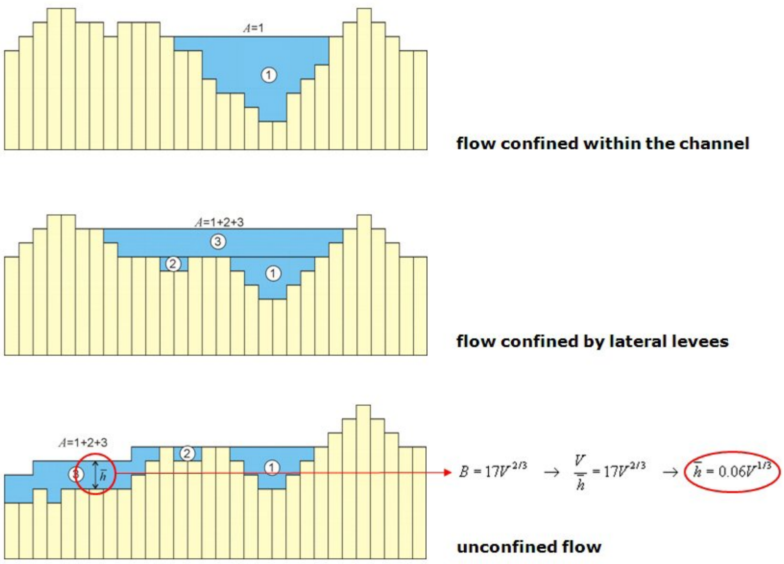

Figure 3. Sketch of the model.

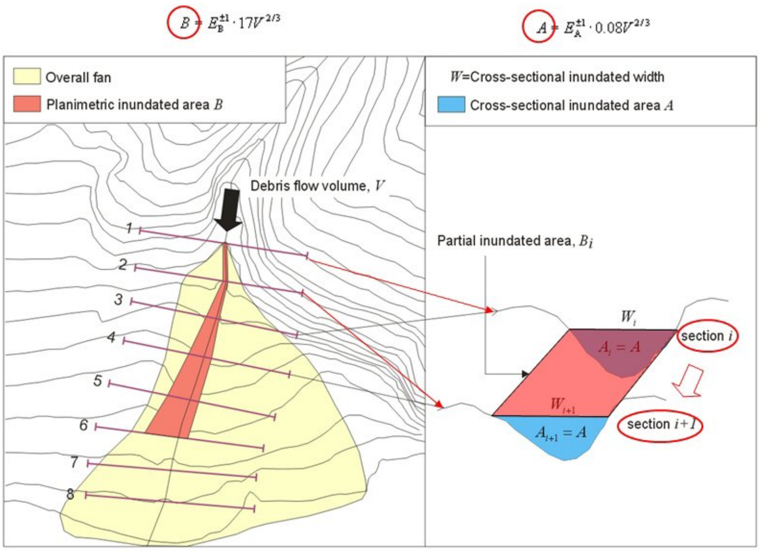

Figure 4. Schematic drawings illustrating how DFLOWZ computes the inundated cross-sectional flow area in three hypothetical cases. A=inundated cross-sectional area.

U5 – Debris flow paths and deposition areas by cellular automata model

A 3D numerical model based on Cellular Automata has been set up in order to simulate the evolutive mechanism of debris flows (Segre & Deangeli, 1995; Deangeli, 1997, Deangeli 2008). The model is capable to analyse debris flows from the triggering to the deposition phase in both cases: confined and unconfined flows.

The computational model describes the flow of a granular material (debris) which moves on a rigid substratum. A vertical averaged description (no variation of the debris properties in the vertical direction z) has been adopted. The computational domain is discretized in elementary cells of finite size. In each one the state of the system is specified by the values of some representative quantities. These include: the height of the impermeable rigid bed, the amounts of water, gas and of granular solids in the cell; the density of the solid liquid mixture and the mechanical properties of the phases. Each cell is considered connected with a number *b* of its nearest neighbors. At each discrete time step some material can be transferred to those neighbors, according to rules which takes into account the local slope in the neighbors directions. The whole lattice is thus viewed as a network of elementary slopelets, each one with its characteristic slope due to the different topography and debris accumulation. The system evolution rule is based on the solution of the differential equations that govern the phenomenon. Different constitutive laws can be implemented in order to represent the characteristic behavior of the water debris mixtures.

The cellular automata model has been used to back analyze granular flows occurred in northern Italy (Deangeli & Grasso, 1996), and to forecast possible scenarios in tailing slopes (Deangeli & Giani, 1998).Figures 5a,b reports two different stages of a simulation performed with Cellular Automata Model.

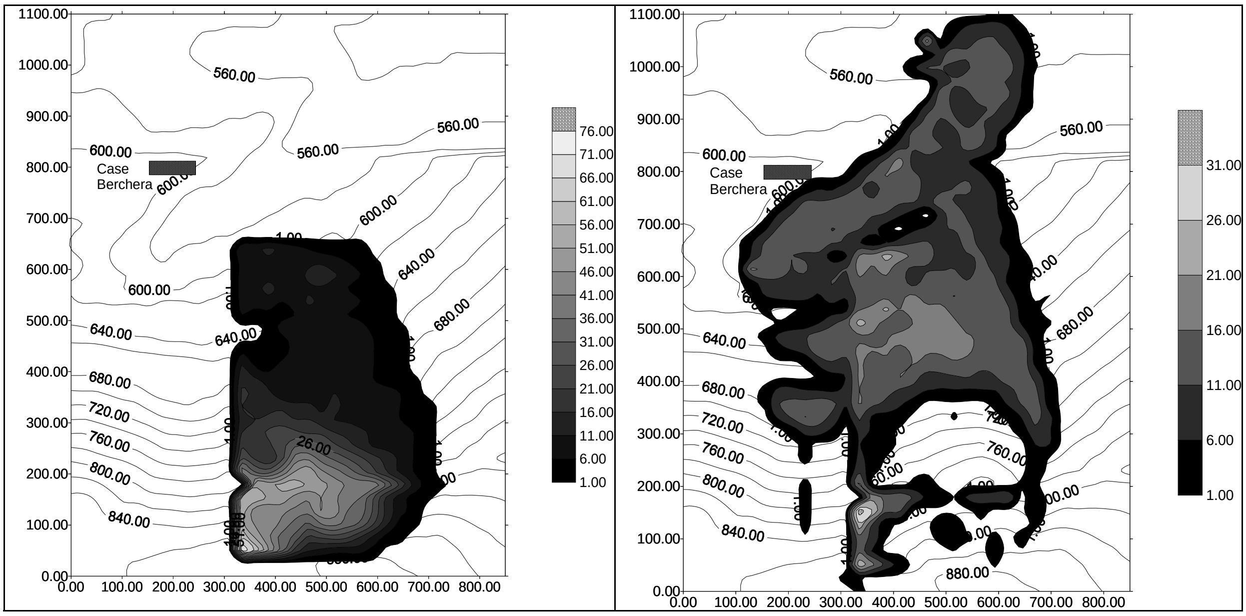

Figure 5. a) Initial configuration of the potential unstable material. Different grey tonalities indicate different thicknesses (in meters) of the debris material. b) Final configuration of the slope. Different grey tonalities indicate different thicknesses (in meters) of the debris material.

U6 – Debris flows impact model

To estimate the impact force of a debris flow against a concrete structure observations are required. Currently it is not possible to develop models only based on theoretical considerations.
The observations and experiments can be distinguished into observations under real-world conditions and experiments in laboratories. The observations under real-world conditions allow the measurement of impact forces of real debris flow events. Examples of such measurements can be found by Zhang (1993) in China, Hübl et al. (2006) in Austria or Wendeler et al. (2007) in Switzerland. However the measurement of further indicators, such as speed, density or flow height is often complicated. Also the time of the debris flow is difficult to predict. Therefore besides field measurement also experiments in laboratories are carried out. These experiments are mainly miniaturized experiments, as real size debris flows experiments are not virtually possible to be carried out in laboratories.

To estimate the impact force of debris flows against barriers different models exist. They can be classified into hydraulic and solid collision models. The hydraulic models are further separated into hydro-static and hydro-dynamic models. Examples of hydro-static models are formulas by Lichtenhahn (1973) and Armanini (1997). Still, in practice the simple formula by Lichtenhahn (1973) is very popular, because only the debris flow height is required. Mixed models considering hydro-static and hydro-dynamic elements can be found from Kherkeulitze (1967) and Arattano & Franzi (2003).

Besides the hydro-related models also solid body impact models are used to estimate debris flow impact forces. Here a shift towards rock fall force estimation can be found. The solid body impact models are mainly based on the Hertz model assuming elastic material behavior. However, also alternative models consider-ing visco-elastic and elastic-plastic behavior are known (Kuwabara & Kono, 1987; Lee & Hermann, 1993; Walton and Braun, 1986; Thornton, 1997). Furthermore some publications use the Kelvin-Voigt model based on spring-damper-systems.

Hydro-dynamic models do not perform very well with low velocities and low Froude numbers (figure 6) . This is understand-able since hydro-dynamic effects are not dominating in hydro-static pressure condi-tions. On Froude numbers higher 2 however, hydro-dynamic models work very well. In contrast, hydro-static models are very appropriate for low Froude numbers, less then 1. For higher Froude numbers and velocities impact forces are underestimated. It can be summarized that hydro-static and hydro-dynamic models do not perform very well in Froude region found in field data.

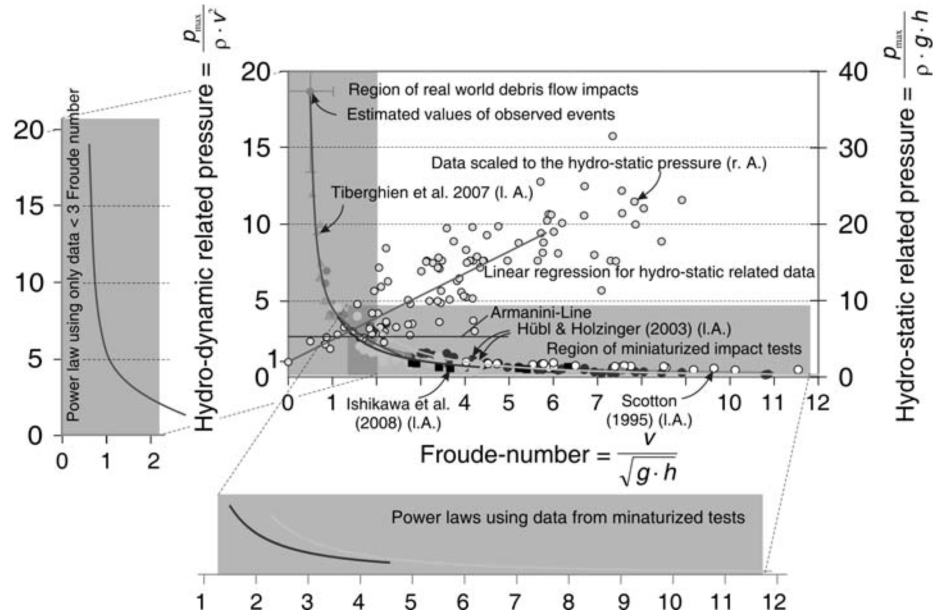

Figure 6: Relationship between debris flow impact force and Froude-number considering field data as well as miniaturized laboratory tests.

The design engineer has to choose from the variety of models. For this selection the models should fulfil some general requirements:

1) Models should be convergent, meaning that with increasing quality of input data the quality of the model result should also increase.
2) Models should be robust, meaning that small changes in the input data should yield only to small changes in the results. Even further the model may perhaps applied in input data regions, in which it was not originally developed.
3) Models should not have a systematically error meaning that the average sta-tistical error is zero.

Furthermore model requirements:

4) The input data for the models has to be either computational able or meas-urable. Even further input data with high weighting inside the formulae should be more precisely known than the other input data.
5) The model should be easy applicable and be usable in practice.
6) The model should at least partially have some theoretical background.
7) The model should be chosen according with historical models, if these his-torical models have been proven of value.
8) If two models reach the same accurateness, the model with less required in-put data should be chosen.

As shown already, all introduced models consider of significant errors in some re-gions of the Froude-number. However, it is then very important to clearly state the application limits. Some of the inherent model errors should be stated clearly to better understand the model capability.

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