MODELING THE DEBRIS FLOW EXPANSION ON ALLUVIAL FAN AREAS
A COMPARISON OF DIFFERENT MODELING APPROACHES

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ABSTRACT

Numerical models represent a tool commonly used to delineate hazard areas affected by debris flows activity. There are several modelling approaches documented in the literature, their applicability depends largely on a series of factors, such as e.g. the mixture rheology and alluvial fan or transport and deposition area topography.

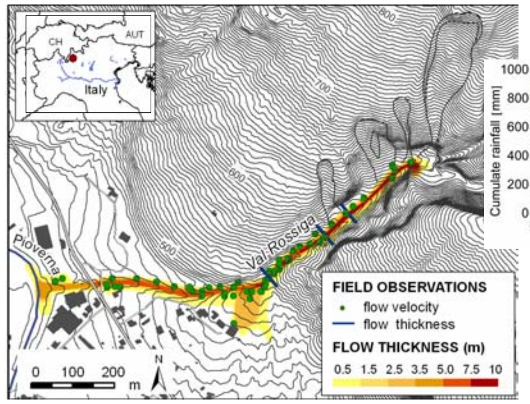
We applied two different numerical models to simulate the well documented debris flow event of the Rossiga Valley (Italian Southern Alps) of November 2002. The event mobilized about 90'000 m^3 of material and spread it over the alluvial fan, damaging 3 buildings and killing some livestock.

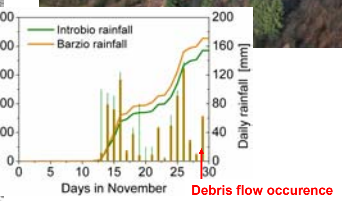
The models are both two-dimensional, but differ greatly in their approaches, how the debris flow expansion is modelled. The first model is a rather simple, empirical model (DFWalk), based on a multiple flow direction algorithm for the flow routing and a two-parameters approach for the debris flow velocity (Gamma, 2000). The second one, (Flo 2D) is physically based, and models the expansion of a non-Newtonian single phase flow based on a given inflow hydrograph (O'Brien et al., 1993).

The two models were applied to the Rossiga Valley debris flow event, and their outputs were compared. The Flo 2D model is able to replicate the inundation extent and flow velocity, but it requires more input data and computational time. The model results are very sensitive to the imposed input data. The DFWalk model needs less input data, but it seems not useful at replicating huge events such as the Rossiga debris flow. The model results are sensitive to the topography and the grid cell size.

THE DEBRIS FLOW EVENT

The Rossiga debris flow occurred on 29th November 2002. 770 – 850 mm of precipitations were recorded the 2 previous weeks. The rainfall event triggered in the same area a number of shallow landslides, which evolved rapidly with high water content. The debris-flow event initiated after the failure of the last and major of these landslides.

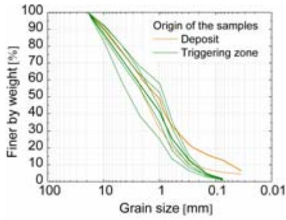


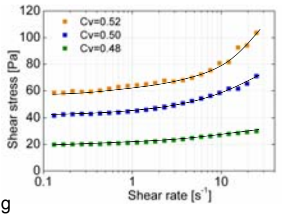


Debris flow occurence

Event dynamics and timing were reconstructed by field evidence and eyewitness account. The debris flow has a total volume evaluated in 80,000 - 90,000 m^3, and the flow thickness reached 7 - 9 m in the channel. The flow velocities were estimated to be of 8-10 ms^{-1}, by means of forced vortex equation for flow through bends. These provide peak discharges ranging between 450 - 500 m^{3}s^{-1}. The thickness of the deposit reached 3-3.5 m in the inundation area. Deposition mainly took place in a urbanized fan area damaging 3 buildings, destroying a bridge and partially damming the main river. We fitted the numerical-modeling results on flow depths and velocities estimated in the field.

The debris flow material is sandy-gravel with a medium-low clay to silt content and boulders up to 5 m in diameter. Sieve analyses were performed on eight samples taken from the deposit and from the source zone. We obtain the grain-size distribution for the fraction passing the 20 mm mesh, which represents 30-40% of the total amount.





We applied the Ball Measuring System, installed in the Paar Physica MCR 300 rheometer, to assess the rheological behavior of two samples coming from the deposit and from the triggering zone (grain size distributions indicated by thicker lines in the figure). The Bingham model best describes the flow curves at shear rates exceeding 5-10 s^{-1}. The viscosity and yield-strength parameters to be used in the numerical model were obtained by fitting experimental data.

MODEL DESCRIPTION

Flo 2D

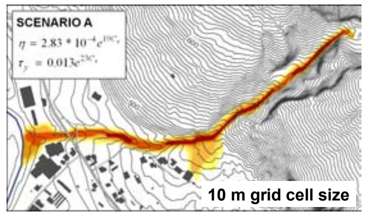
Flo 2D is a physically based two dimensional model for the forecast of debris flows runout and inundation limits (O'Brien et al., 1993). The model describes the routing behaviour of a bulked inflow hydrograph like a homogeneous, one-phase material over a rigid bed. The resistive component of the momentum equation follows a quadratic rheological model that combines in a linear sum the viscoplastic terms and a quadratic, inertial term, which depends on an equivalent distributed Manning's n-value. The model postulates a Bingham behavior with the yield stress and dynamic viscosity parameters depending on sediment concentration.

DEBRIS FLOW PROPAGATION

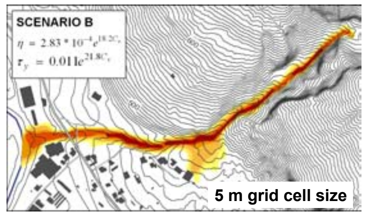
volume	80000-90000 m^3
peak discharge	450-500 m^3 s^{-1}
travel time	4-8 min
base time	5-10 min
velocity	8-10 m s^{-1}

DEBRIS FLOW DEPOSITION

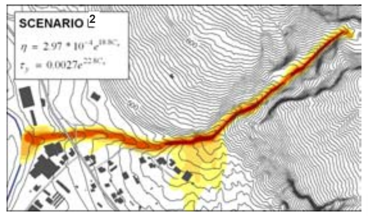
maximum height in the channel	7-9 m
thickness in fan apex	up to 3 m
yield strength	4000 +/- 200 Pa

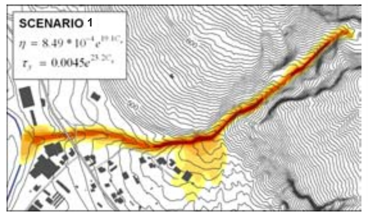


10 m grid cell size



5 m grid cell size





MODEL CALIBRATION

We route an inflow hydrograph with a peak discharge of 485 m^{3}s^{-1} giving a total volume of 90,000 m^3 on two different grids spaced by 10 m (Scenario A) and 5 m (Scenario B). The calibration have been performed on the coefficients taking into account for the exponential dependence of the viscosity, η_p, and the yield strength, τ_y, on sediment concentration by volume, Cv:

$$\eta_p = \alpha \, e^{\beta Cv} \quad (1)$$

$$\tau_y = \gamma \, e^{\delta Cv} \quad (2)$$

We perform two simulations on the 10 m cell-size grid assuming, as input data for the model, the rheological coefficients derived by direct measurements on the deposit material.

MODELING RESULTS

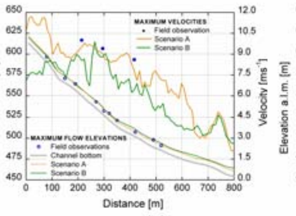
1. After the trial and error calibration, the model replicates satisfactorily the inundation areas and the flow velocities.

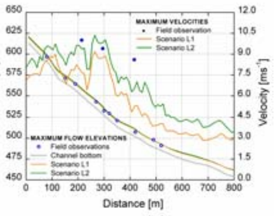
2. The coefficients resulting from the back analyses vary depending on the imposed routing condition (i.e. grid cell size-Scenario A and B). The differences in the coefficients could be significant: in our case, the linear coefficient for the viscosity (α in eq. 1) varies by one order of magnitude.

3. The model routed by using the laboratory coefficients for the rheological parameters (Scenario 1 and 2) results in a larger spreading for the inundation area, and a lower thickness for the deposits than the Rossiga event.

4. The viscosity mainly affects distribution of the material deposited along the whole flow path. Lower viscosities induce higher flow mobility and thus determine the ratio among the debris volume deposited with respect to the volume out flowing from the grid system.

5. The yield strength influences the inundation extent and the average thickness of deposition.





MODEL DESCRIPTION

DFWalk

Dfwalk is a conceptual model for calculation of the area involved by debris flows inundation. The model consists of a combination of empirical and statistical approaches. The model works as follows:

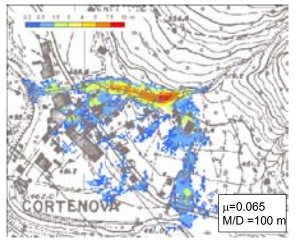
Calculation of the path of the Random Walk for every starting cell. From the user-defined starting cell, a number of debris flow pathways (Random Walk) are modelled by a combination of single and multiple flow direction algorithms. The velocity is calculated according to the 2-parameter friction model developed by Voellmy and further modified by Perla et al. (1980). The two parameters of the model are the sliding friction coefficient μ and the Mass-to-drag ratio M/D.

Calculation of the deposition of the material. The deposition in a cell starts for slopes or velocities less than user-defined threshold value. The total amount of deposition results from the sum of the sedimentation of each Random Walk.

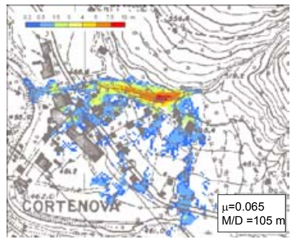
The results of the model are 3 maps representing the expansion probability of the random walks, the mean velocity reached in each cell, and the sediment depth in the deposition area.

MODEL CALIBRATION

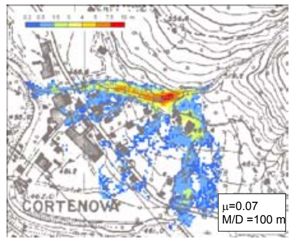
The calibration of the event was performed mainly on 4 parameters: the μ and M/D parameters required by the Perla's model and the slope and velocity values that defines thresholds for sedimentation to initiate. These results were obtained with a 5 meters resolution of the Digital Elevation Model. The chosen values for the other parameters are summarized in the following table.



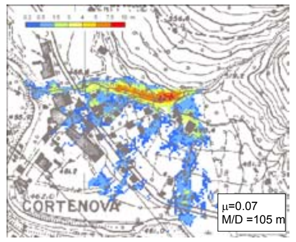
μ=0.065
M/D =100 m



μ=0.065
M/D =105 m



μ=0.07
M/D =100 m



μ=0.07
M/D =105 m

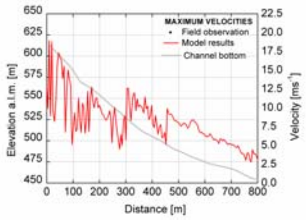
Input parameters

# Random Walks (RW)	750
Threshold slope [%]	25
Debris volume for RW [m^3]	120
Maximum sedimentation for cell [m]	1
Velocity threshold [ms^{-1}]	7
Slope threshold [%]	25

MODELLING RESULTS

The model results are largely affected by the topography, in particular at the fan apex, where the slope decreases sharply (26-28% to 14-17%).

The velocity threshold for sedimentation has an higher influence on the area affected by sedimentation rather than the slope threshold. This slope threshold is useful because it helps the sediment depth to be less dependent on the irregularity of the velocity.

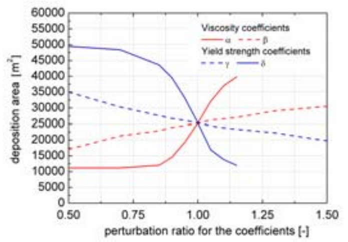


Dfwalk does not recognize the difference between hydraulic behavior of the debris flow along the river bed and on the alluvial fan, and the flow path it is essentially controlled by the local topography. This results in:

1. the runout in the fan area is independent from the channel.
2. higher flow velocities with respect to the measured ones, in order to allow the flow to reach the end of the channel, and to avoid high sedimentation to occur before the fan apex.

For these reasons the Dfwalk model is not able to reproduce satisfactorily the extents of the deposition area.

COMPARISON

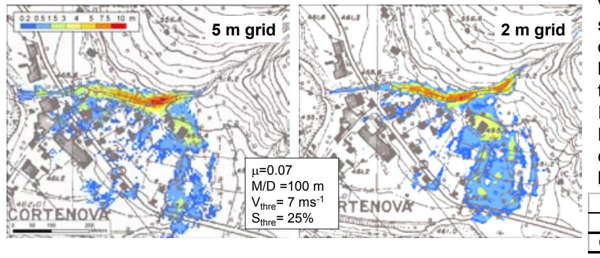


The **Flo-2D model** reproduces the Rossiga debris-flow event in a satisfactorily. The results are achieved after a calibration of the unknown input data. Their values can change up to one order of magnitude at varying several routing conditions. In the range of variability of the rheological coefficients the inundation extent and mean flow thickness vary non linearly.

	Yield strength		Viscosity	
	α	β	α	β
Back analysis	(1.1 - 1.3) *10^{-2}	21.8-23	(2.8 - 28) *10^{-4}	18.2-19
Rheometry	(2.7 - 4.5) *10^{-3}	22.8-23.2	(3 - 8.5) *10^{-4}	18.8-19.1

The **Dfwalk model** is mainly controlled by topography. Any variations in the parameters results in a velocity distribution and in a deposition extent which reflects the local morphology. Increasing the DEM resolution (from 5 to 2 m) the sensitivity of the model to the 4 investigated parameters increases. Another important remark is the choice of the number of Random Walks. As the cell grid size decreases the volume associated to each Random Walk has to be decreased in order to allow for all the material to be deposited.

As a consequence of the increased number of Random Walks, the 2 m DEM provides a wider area of expansion in the fan.



μ=0.07
M/D =100 m
V_{thre}= 7 ms^{-1}
S_{thre}= 25%

The subdivision of the total debris-flow volume in a number of smaller events seems to be a limit at replicating the deposition process of debris flows, because it enhances the role exerted by topography over the real flow behavior. In particular for huge events, such as the Rossiga event, the deposition is controlled by debris volume more than by local morphology.

Perla's coefficients		Sedimentation thresholds	
μ	M/D [m]	velocity [ms^{-1}]	slope [%]
0.055 – 0.07	90 – 105	7 – 10	15-30

CONCLUSIONS

The Flo-2D and DFWalk models for the calculation of the area involved by debris-flows inundation have been compared. For debris-flow events constituted by a significant amount of coarse boulders, the laboratory derived rheological parameters can not be used as input data for the model, and a back analysis has to be performed. The model outcomes are highly sensitive to the variability of the rheological parameters introduced in the model. So that, the model requires a well known debris flow event to perform for the calibration of the unknown parameters.

DFWalk requires a less detailed characterization of the debris flow event. The main advantages with respect to Flo-2D model are a shorter computation-time and minor data-input requirements. It seems to be more suitable than to be used as a tool for forecast of the possible inundation area at a less detailed scale, and when recent event to be used for the calibration lacks. The DFWalk model has some limit at simulating events of large magnitude, when the morphology is complex and the channel is able to convey large volumes.

For both models the choice of the best fit parameters is sensitive to the adopted cell size. At increasing the grid resolution, the parameters used in Flo 2D model change by one order of magnitude. DFWalk is less sensitive to the grid cell size, even if at increasing the spatial resolution, a similar perturbation in the input data produces greater changes in the model results. Due to the high importance of topography, a minimum grid resolution of 5-10 m is suggested.

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