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DATA UNCERTAINTY AND VARIABILITY IN MODELING DEBRIS FLOW PROPAGATION

R. SOSIO & G.B. CROSTA(*)

(*)University of Milano-Bicocca, Department of Scienze Geologiche e Geotecnologie, Italy

ABSTRACT

We replicate the propagation of the Val Rossiga debris flow (November 2002, Central Italian Alps), a 90,000 m^3 event triggered by a rapid retrogressive landslide with high water content. The rheological model combines in a linear sum the viscoplastic terms of the Bingham model and a quadratic inertial term. The model requires as input data the bulked hydrograph and the empirical coefficients which describe the exponential dependence of the rheological parameters (i.e. Bingham viscosity and yield stress) on sediment concentration. We provided these data through different methods. Alternative hydrographs were produced by simulating the propagation of the triggering landslide according to different rheologies (i.e. rigid block model, frictional material, and Voellmy material). The rheological parameters are either determined by back analyses and directly through laboratory measurements and field investigation. Laboratory measurements were performed using a Ball Measuring System and a vane apparatus connected to a rotational rheometer on three samples from different sectors of flow path (i.e. source, channel and fan deposit). The samples were analyzed at varying the solid concentration and the grain size included in the tested suspensions (maximum grain size of 0.425 mm). The alterative conditions assumed for the input data were modeled on topographies of 5 m and 10 m cell-size. The seven scenarios we obtained were optimized by back analyses of the rheological parameters.

Among the condition tested, the largest uncertainty is related to the initial hydrograph, which the model is very sensitive to (particularly with respect to peak discharge). Moreover, the hydrograph input data are unknown in most of the cases and a-priori derivable only with large approximation. The alternative inflow hydrographs require a variation larger than one order of magnitude in the values of the rheological parameters obtained by the back analyses. The rheological properties measured directly on samples of varying composition (e.g. origin and grain size included) fall in most of the cases within the range of uncertainty defined by the alternative inflows considered. Overall, the vane geometry is preferable against the Ball Measuring System. The latter suffers for more narrow testable conditions, more marked experimental limits, and produces results which are more scattered than the vane geometry.

Key words: *numerical modelling, rheometry, viscosity, yield strength*

INTRODUCTION

Modeling debris-flow propagation requires assumptions and simplifications because of (i) the lack of data which are either not measurable or not available, (ii) the variability of the involved material, (iii) the difficulty at characterizing the flow behavior, and (iv) the limitations of the adopted rheological kernels. Although all the necessary assumptions cause the

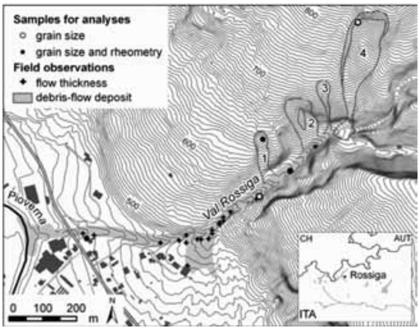

Fig.1 - The Rossiga debris flow event (80 000–90 000 m3) initiated from landslide 4. The debris flow deposition (grey area) largely took place at the fan apex and at the confluence with the Pioverna river. Points of measurement of the maximum flow thickness, used for comparison of the modelling results (Figure 6 b) and sampling points for the laboratory analyses are shown

model results to diverge more or less from reality, an evaluation of the uncertainties generally lacks.

Among these criticalities, the rheological assumption (i.e. one, two- phase; resistance law) and the mode of determining the rheological parameters (i.e. direct measurements, back analyses) have been deserved large attention (Iverson, 2003). The choice of the total hydrograph (i.e. water discharge and associated sediment discharge) to be routed in the model can be equally critical, particularly with respect to the highest sediment concentration adopted (Berger *et alii.*, in press).

In this paper we present the results of the analyses conducted on a well documented event which occurred on November 2002 along the Rossiga valley, Valsassina, Central Italian Alps (Fig. 1, Sosio *et alii.*, 2007), adopting a one-phase model, which assumes a Bingham plastic rheological behaviour (O'Brien *et alii.*, 1993). The event was both described by eyewitness and documented by field surveys.

The debris flow originated from the failure of a rapid, retrogressive landslide with high water content (Crosta *et alii.*, 2006). Other failure events had occurred in the previous days, delivering the failed material in the Rossiga channel.

The debris flow material is poorly sorted with medium–low clay to silt content. As a consequence, both the viscous and the frictional–collisional effects can be relevant, thus posing the event in an intermediate condition between the one-phase and two-phase conditions, and makes difficult a rheometrical characterization of the material by means of direct measurements. The complexity of the event evolution and the different origin of the debris material, pose an high degree of uncertainty at reconstructing the proper conditions for the modelling, which is only partly compensated by the large amount of available data.

We propose different alternative choices for unavailable or uncertain data (i.e. total inflow hydrograph, rheological parameters), and we compare models at different topographical resolution. As a result we evaluate: (i) which assumptions better approximate the debris flow evolution; (ii) which aspect of the modeling (i.e. initial inflow, rheological description) is more critical by comparing the range of variability the alternative conditions tested and the final results produced thereof; (iii) the capability of different methods of determining the rheological parameters; (iv) the grain size composition which better approximates the flow behavior; (v) which level of detail in the input data is relevant for modeling purposes.

THE ROSSIGA DEBRIS FLOW EVENT

At the end of an exceptional rainy period which affected the Central Italian Alps, four landslides were triggered on the right-hand side of the Rossiga Valley (Valsassina, Lombardy, Sosio *et alii.*, 2007) between 27 and 29 November (Fig. 1). The debris flow originated from the failure of the main and uppermost landslide (Crosta *et alii.*, 2006). The landslide ran up on the opposite valley flank for about 15 m, slightly damming the Rossiga creek. Field evidence and eyewitness accounts indicate that the transformation of the sliding mass into a fluid-like, rapidly moving debris flow was instantaneous, as predicted for 'high-porosity' soils (Iverson, 2000). This excludes the hypothesis of a debris flow resulting from the breach of a dam.

The debris flow travelled along a channel partially filled by the accumulations of previous landslides (the total volume detached by the landslides were about 200,000 m^3). The event magnitude was evaluated as 80,000–90,000 m^3. Measurements of super-elevation of the flow surface by the mudlines left during the peak discharge at the channel bends (Johnson & Rodine, 1984; Hungr *et alii.*, 1984) suggest flow velocities of 8–10 m s−1. The debris flow evolved into a main surge, eventually followed by a smaller, secondary one, and it took between 4 and 8 minutes to travel 800 m from the initiation point to the confluence of the Rossiga channel into the Pioverna river, in the main valley.

Field measurements revealed a maximum flow thickness along the channel of 10 m and a deposit depth of 3-5 m in the fan area. Mudline observations along the path revealed a nearly constant maximum flow cross-sectional area. A tabular and lobate deposit about 60 m wide and 80 m long, with an average thickness of 2-5 m, formed on the 6° sloping surface of the fan. Based on field evidence, we empirically estimated yield strength (Johnson, 1970; Johnson & Rodine, 1984) and viscosity (Johnson & Rodine,1984) ranging between 4000 ± 200 Pa, and 108–134 Pa s, respectively (Sosio et al., 2007).

The debris-flow material is mono-lithologic, consisting of Verrucano Lombardo (Permian conglomerate and sandstone), derived both from the original landslide and from the sediments available along the channel. The material is poorly sorted, varying from clay to boulders up to 5 m in diameter. The deposit is massive and matrix supported.

THE NUMERICAL MODELING

We performed a series of numerical simulations using the physically based Flo-2D model for the forecast of debris flow runout and inundation area (O'Brien et al., 1993). The model describes the routing behaviour of a bulked inflow hydrograph as a homogeneous, one-phase material over a rigid bed. The flow behaviour is provided by matrix properties and follows the Bingham model.

MODEL DESCRIPTION

Flo-2D is a flood-routing model, which uses a dynamic-wave momentum equation and a finite-difference routing scheme on an Eulerian framework. The model routes a user-defined water discharge and the associated solid discharge on a square elevation grid according to a quadratic rheological model. The shear stress, τ, results by a linear sum of the viscoplastic terms of the Bingham model and a quadratic, inertial term, referring to the turbulent and dispersive stresses:

$$\tau = \tau_y + \eta \gamma + C \gamma^2 \qquad (1)$$

where is the shear rate, C is the inertial shear stress coefficient, which depends on an equivalent Manning *n*-value. The model neglects any frictional effect due to direct contacts among the coarse clasts.

The yield strength, τ_y, and viscosity, η, terms are scaled on user-defined empirical coefficients taking into account the exponential dependence of the rheological parameters on sediment concentration (O'Brien & Julien, 1988; Major & Pierson, 1992; Coussot & Piau, 1994):

$$\tau_y = \alpha_\tau e^{\beta_\tau C_V} \qquad (2)$$

$$\eta = \alpha_\eta e^{\beta\eta C_V} \qquad (3)$$

where C_v represents the sediment concentration by volume.

MODELING SCENARIOS

We applied the Flo-2D routing model to the Rossiga event, assuming that the overall flow behaviour can be approximated by one-phase assumption and the viscoplastic behaviour assumed into the numerical model is consistent with the results of the rheological analyses performed on the debris-flow samples for shear rates exceeding 5–10 s−1 (Sosio *et alii*, 2007; Sosio & Crosta, 2009).

We reconstruct the topography by resampling a 1 m resolution LIDAR DEM, taken after the event into a 5*5 and 10*10 m cell-size grids. We defined the channel geometry by interpolating 24 surveyed cross-sections spaced to represent about 30 m river reaches. Scour or aggradation processes along the channel have been neglected. Both these effects have been relevant as indicated by the distribution of the debris along the channel cross section, and by the roughness of the channel bottom after the event. In particular, the delivered sediment at the confluence of the main landslides (Fig. 1) probably affected the flow dynamics, both supplying material and constraining the flow path on the opposite valley flank.

Different modelling scenarios are performed at changing the total inflow hydrograph originated from the transformation of the landslide into debris flow and for the rheological coefficients that empirically accounts for the exponential dependency of the material properties on the sediment concentration (α and β in eq. 2 and 3).

The alternative total inflow hydrographs consider different modes of propagation for the initial landslide (source 4 in fig. 1) before the transformation into debris flow. They are: (A) rigid block model, (B)

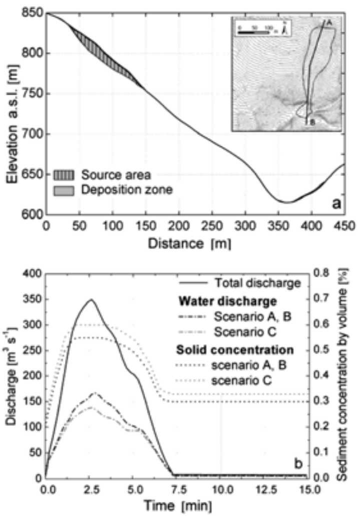

Fig. 2 - (a) Pre- and post-failure longitudinal profiles for landslide 4, (Figure 1). The thickness of the removed material in the source area was used to derive the inflow hydrograph required in the numerical model. (b) Inflow hydrographs routed by the numerical model. At varying bulking concentrations the total discharge was kept constant. Refer to table 1 for scenario's names

Voellmy, and (C) frictional rheology. The alternative mode for determining the empirical coefficient describing the rheological flow behaviour (eq. 2 and 3) are (A) back analyses of the documented event, direct measurement by (B) ball measuring system (BMS) and (C) vane rheometrical apparatus, at changing the sample and the investigated grain size.

DEFINING THE INITIAL DISCHARGE

Field observations and eyewitness accounts revealed the development of the debris flow as a main surge followed by a low-discharge tail. Following this observation we derived an inflow hydrograph with a single peak discharge. A peak discharge of 350 $m^3 s^{-1}$ has been estimated from the flow velocity and cross sectional area in the vicinity of the debris flow initiation, and the suggested base time is about 7.5 min (Sosio *et alii.*, 2007). The maximum estimation of the debris removed from the source area is about 80,000-90,000 m^3. This value does not include erosion along the channel.

According to the landslide triggering mechanism, we loaded the water discharge with sediment at large mean (40–45 per cent in volume) and maximum (55-60 per cent in volume) solid concentrations. The maximum solid concentration slightly precedes the water peak discharge (O'Brien 2003). Bulking the water discharge with variable solid concentration is aimed at obtaining a total inflow volume of approximately 90,000-95,000 m^3. This range of values exceed the estimation of the volume detached from the landslide which initiated the debris flow, as to include erosion of the material detached by the previous landslide events which was available along the channel. The alternative inflow hydrographs consider different mode for the propagation of the initial landslide, and are: (A) rigid block model, (B) Voellmy rheology, and (C) frictional rheology. The debris flow hydrographs produced by the alternative mode of propagation of the initial landslide change by their peak discharges and time durations.

RIGID BLOCK MODEL

The total inflow (water and sediment) hydrograph is derived from the pre- and post-failure longitudinal profiles of the failed slope, assuming a shape equal to the landslide depth at the source area (Fig. 2a). From the depth–longitudinal profile we derived a discharge-time hydrograph (fig 2b), considering a constant source area width and assuming that the sliding material has been moved as a single, rigid, mass from the scarp to the valley. We scaled the bulked, depth profile as to obtain a total (water and solid) hydrograph with a 350 m3 s−1 peak discharge and a 7.5 minutes base time.

FRICTIONAL AND VOELLMY MODELS

We modelled the initial landslide (#4 in figure 1) using a quasi-3D model for simulation of landslide motion (McDougall & Hungr, 2004). The model assumes the internal rheology as frictional and the basal rheologies as frictional (eq 4) and Voellmy (eq. 5), alternatively:

$$\tau = \sigma \left(1 - r_u\right) \tan \phi \tag{4}$$

$$\tau = \sigma\mu + \frac{\rho g v^2}{\xi} \tag{5}$$

The relationship between the shear force, τ, and the effective normal stress, σ is described through empirical coefficients to be

find by trial and error calibration. They are: the pore-pressure ratio, ru, and the dynamic friction angle, φ, in the frictional model, and the friction co-

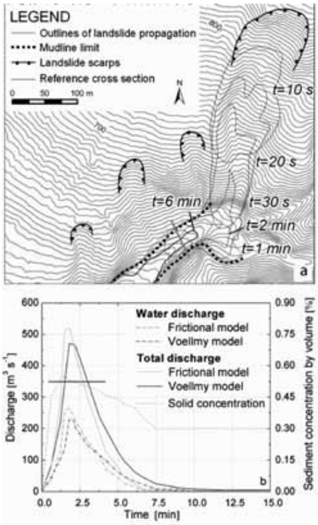

Fig. 3 - *(a) Time evolution of the propagation of landslide 4, (Figure 1) assuming the Voellmy rheological model. The thickness of the material passing through a cross section at the head of the valley (indicated in the figure) was used to derive the inflow hydrograph required in the numerical model. (b) Inflow hydrographs routed by the numerical model assuming a Voellmy and frictional rheology for the landslide propagation. At varying the rheological model, the shape of the total and water hydrographs changes. The peak discharge for the rigid block models is indicated by the line*

efficient, μ, and the turbulence coefficient, ξ, in the Voellmy model.

We modelled the motion of a shallow landslide of about 91,000 m^3 of material. The model geometry and the local depths of the detached material have been derived by the pre and post –event topographies. The landslide front takes about 20-25 seconds from the initial detachment to reach the head of Rossiga valley. At the confluence into the valley, the debris has a velocity of 18 ms-1 (assuming the frictional rheology, φ=32°, u_r=0.25) and 14 ms^{-1}

(assuming the Voellmy, μ,=0.21 ξ=50 ms^{-2}). In both the models, part of the material runs up on to the opposite valley at the height indicated by the observed mudlines (i.e. about 15 m, Fig. 3), and then continues its motion downstream, channelled along the valley. This behaviour is confirmed by the field observations which suggest an immediate transformation of the landslide into debris flow and exclude the debris-flow initiation by breaching of a landslide dam constituted by the landslide material accumulated in the valley.

	Cell size	Inflow assumption	Max C_v	Basetime	Peak Discharge
	[m]		[%]	[min]	[m^3s^{-1}]
Scenario A	10*10	Rigid Block	55	7.5	350
Scenario B	5*5	Rigid Block	55	7.5	350
Scenario C	10*10	Rigid Block	60	7.5	350
Scenario D - V	10*10	Dan, Voellmy	55	7.0	465
Scenario D - F	10*10	Dan, Frictional	55	6.0	508

Tab. 1 - Modelling conditions for each scenario

We reconstructed the total hydrograph according to the debris volumes passing through an imaginary cross section at the head of the Rossiga channel through time (fig 3a). Time intervals of 6 minutes (assuming a frictional model), and 7 minutes (assuming a Voellmy model) are required for the detached debris to arrive entirely into the valley. The peak discharges resulting from the numerical modelling of the landslide propagation are approximately 500 m3s-1 for both the models (Fig 3b), thus resulting slightly higher than the discharge estimation in the field (350 m^3s^{-1}), for the rigid block assessment. This difference can be explained considering the wave attenuation during its propagation downstream (Pierson 1986;Arattano & Moia, 1999). The obtained base time (table 1), is comparable to observations

DEFINING THE RHEOLOGICAL PARAMETERS

The empirical coefficients which describe the exponential relationship of the yield strength and viscosity with solid concentration are alternatively defined by (A) back analyses and (B) direct measurement of the rheological properties of the material for three samples at varying solid concentration. The samples were collected along the flow path, from the landslide scarps (source areas 1 and 4) and from the deposit (Fig. 1).

More than providing the empirical coefficient required for the modelling, the rheometrical characterization allows to verify the rheological behaviour assumed in the model. The material has a relevant and variable content of fines (5-15% of the fraction finer than 20 mm, Sosio *et alii.*, 2007), which pose the event at the boundary to be considered as one-phase. For the diverse samples tested, the flow curves are best approximated by the Herschel-Bulkley model, shear thinning or shear thickening depending on the grain size considered for the analyses (Sosio &Crosta, 2009).

The measurements have been performed with the

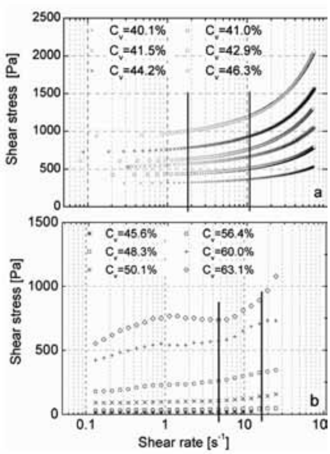

Fig. 4 - Flow curves for a sample collected at the source area on fraction finer than 0.425 mm (source 1, figure 1). The data refers to the results obtained performing the analyses with (a) the vane geometry, (b) the ball measuring system (BMS). The different tools have different range of applicability with reference to the shear rate to be applied and the solid concentration of the suspension to be tested. In the graphs, the vertical lines indicate the shear rate interval where the material viscosity has been determined as a mean value

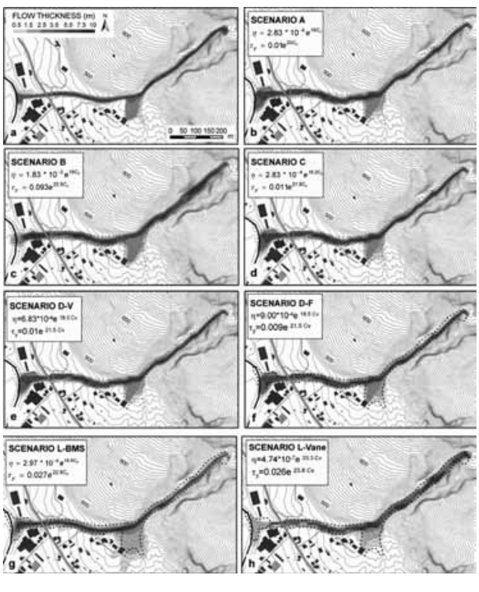

Fig. 5 - Deposit distribution of the Rossiga debris-flow event: (a) field reconstruction of the flow thickness and (from b to h) computed flow thicknesses for different modelling conditions compared to observed limits (dashed lines) for the different scenarios

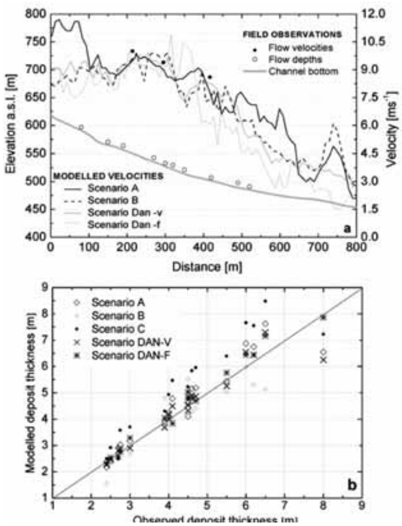

Fig. 6 - (a) Flow velocity along the channel compared for the modelled scenarios. Dots define peak flow velocities computed at the channel bends based on the mudline left during the peak discharge (Johnson and Rodine, 1984; Hungr et al., 1984). (b) Comparison between measured and computed values for the deposit thickness. The location of the measuring sites is shown in Figure 1 (crosses)

Ball Measuring System (BMS, Schatzmann *et alii*, 2003, Sosio *et alii*, 2007) and a Vane (Ancey & Jorrot, 2001; Ancey, 2001) installed in the rheometer Paar Physica MCR 300. The standard experiments consisted of measuring the torque required by the material to flow at fixed rotational velocities during time (i.e., stress growth curves), by the material when subjected to a constant shear stress (creep curves) From the stress growth curves we derived the flow curves (Fig. 4) and the deformation undergone.

BACK ANALYSES

The coefficients (α, β, γ and δ in Equations 2 and 3) that define the rheological properties of the material have been back-calculated by a trial and error calibration on the (maximum) flow and (final) deposit thickness, travel time, flow velocities, and depositional areas. The back analysis has been performed at varying modelling conditions (i.e. initial hydrograph, grid cell size; see table 1 for a description of the scenarios).

Figure 5 and 6 show the results of the back analyses for the diverse scenarios considered, whereas figure 7 compares the trend of the rheological parameters obtained by the different methods adopted.

RHEOMETRY: BALL MEASURING SYSTEM

The rheological analyses were performed on two samples, one from the distal portion of the fan, and one from the source area 1 (Fig. 1), considering the fraction finer than 0.425 mm (25–30 per cent of the sieved material) at different solid contents (from 45 to 63 per cent, by volume). We derive the viscosity as the mean slope in the Bingham region of the flow curves (O'Brien & Julien, 1988; Major & Pierson, 1992). Creep curves provide the direct measurements of the yield strength, as the stress value necessary for permanent deformation to occur.

RHEOMETRY: VANE

We investigated the rheological behavior of three samples taken from the debris flow deposit and source area at varying solid concentration (from 38.0 to 54.2% by volume) and grain size distribution. Experiments were performed first on the fraction finer than 0.075 mm. Additional experiments evaluate the effects on the rheological behaviour at varying the grain size distribution of the suspension. These where conducted including sand with different grain sizes (from 0.106 mm to 0.425 mm in size) and percentages (from 10 to 50%) to a suspension constituted of particles finer than 0.075 mm.

The flow curves, obtained in a control rate mode and regularized by the Tikhonov's method (Ancey, 2005), were fitted with the Bingham and Herschel-Bulkley models to derive the rheological parameters The viscosity has been evaluated as the mean slope in the region of the flow curve where there is a linear increase of the shear stress with the shear rate (between 1 and 10 s^{-1}, see fig Fig. 4). We assumed the yield strength as the value obtained by the regularization procedure.

DISCUSSION

Applying any numerical model to natural events has uncertainties related both to unknown input data and numerical computation, particularly when an optimization procedure is not performed. Some data can only be hypothetically postulated (i.e. sediment content and discharges, Manning n-values etc.), others depend on modeller requirements (i.e. cell-size dimension). These parameters can change largely and their choice requires assumptions and simplification which are only seldom supported.

In some cases, perturbing unknown conditions among different scenarios largely affects the results of the back-analysis. The changes eventually determine

	α_η	β_η	α_τ	β_τ
Back analyses				
SCENARIO A	2.83E-04	19.0	1.30E-02	23.0
SCENARIO B	1.83E-03	19.0	9.30E-03	23.5
SCENARIO C	2.83E-04	18.2	1.10E-02	21.8
SCENARIO D-V	6.30E-03	18.0	4.00E-02	21.0
SCENARIO D-F	8.00E-03	18.0	3.00E-02	21.5
Rheometry				
BMS, S1 - 0.425	2.03E-03	18.0	4.00E-03	22.0
BMS, D6 - 0.425	2.97E-04	18.8	1.27E-03	22.8
Vane, S1 - 0.074	2.29E-03	19.1	1.04E+00	15.0
Vane, D6 - 0.075	1.64E-04	19.1	1.50E-02	23.7
Vane, D4 - 0.075	6.80E-04	19.5	4.30E-02	20.1
Vane, D4 - 0.150	2.35E-03	17.2	1.65E-02	20.2
Vane, D4 - 0.250	1.06E-06	28.6	1.80E-03	24.9
Vane, D4 - 0.300	4.74E-07	33.3	2.60E-03	23.8
Vane, D4 - 0.425	2.00E-07	38.6	2.00E-04	29.0

Tab. 2 - Values of coefficients for eq. 2 and 3 obtained through back analyses from numerical modelling of varying scenarios and rheometrical measurement on different samples

large variations into the values assumed by the rheological parameters which results from the back analyses more than to changes in event replication (i.e. flow evolution, final deposition, etc). As an example, reducing the grid cell size from 10 m to 5 m (Scenario A and B) induces an increase of the viscosity by one order of magnitude for the whole range of sediment concentration (see the values of the rheological coefficient in table 2). Smaller cells require larger viscosities to assure the maintenance of subcritical flow through the rough and steep slope topography of the area and the replication of the flow velocity estimated in the field. On the other hand, no relevant variations in the replication of the event were observed.

MODELLING CONDITIONS

The input hydrographs differ among the scenarios (see Fig. 2, 3) by 30% with respect to the total hydrograph, varying the water peak discharge from 350 m3s-1 (Scenario A) to 450-500 $m3s^{-1}$ (Scenario D-V, D-F), and by 10% with respect to bulking, varying the solid concentration by volume from 55% (Scenarios A, D-F, D-V) to 60% (Scenario C). The results for all the scenarios capture the gross features of the debris flow which are either measured (i.e. flow thicknesses, propagation area) or estimated (i.e. flow velocity, yield strength, viscosity) in the field (Fig. 5 and 6, table 3). Among them, Scenario Dan-F and Scenario B best capture the observed thickness both for the deposit (final values) and for the flow mudlines along the channel (maximum values), as suggested by the lowest values of standard deviation (figure 6, b), whereas Scenarios C and Dan-V best recognize the area of propagation (table 4). The field estimation for the velocity with the super- elevation method suggest values of about 8–10 m s^{-1}, but these data are sparse and the method can overestimate by up to 30 per cent the estimated velocity values (IVERSON 1997; WHIPPLE, 1997). On the other hand, the flow velocity resulting from the modelling is very sensitive to local morphology (figure 6 a). Large differences are otherwise observed with respect to the values assumed by the rheological coefficients adjusted by back analyses (table 2).

The viscosity change by one-two orders of magnitude among the scenarios, and larger values are required by larger peak discharges. The yield strength is otherwise less sensitive to variation in modelling conditions. Assuming the frictional and Voellmy model for the propagation of the initial landslide allows obtaining values which are comparable to field estimation both for the viscosities and the yield strength.

	viscosity	yield strength
Field estimations	126 +/- 12	4000 +/-200
Back analyses		
SCENARIO A	10	4053
SCENARIO B	63	3817
SCENARIO C	16	5272
SCENARIO D-V	126	4151
SCENARIO D-F	159	4099
Rheometry		
BMS, S1 - 0.425	40	719
BMS, D6 - 0.425	9	355
Vane, S1 - 0.075	84	3965
Vane, D6 - 0.075	21	6873
Vane, D4 - 0.075	31	5251
Vane, D4 - 0.150	30	1103
Vane, D4 - 0.250	72	1596
Vane, D4 - 0.300	88	3824
Vane, D4 - 0.425	192	3212

Tab. 3 - Field estimated viscosity and yield strength parameters compared against the values of the same parameters resulting from back analyses (evaluated at the maximum Cv adopted in each scenario) and rheometrical measurement (evaluated at Cv=55%). The confidence interval in the field estimation data refers to the uncertainty of the measurement

RHEOLOGICAL BEHAVIOR

The mixture behavior is viscoplastic and it varies markedly with small variations in solid volume fraction, shear rate, and grain size distribution (O'BRIEN A& JULIEN, 1988; PHILLIPS & DAVIES, 1991; MAJOR & PIERSON, 1992). At shear rates lower than 3–5 s^{-1}, shear stress is rate-independent suggesting a frictional behaviour. At higher shear rates, the shear stress increases depending on the grain particle size included within the suspension. We used the Herschel- Bulkley and Bingham models to describe the monotonous increase of the shear stress with the shear rate in this region. At changing the grain size distribution, the behaviour varies from shear thinning to shear thickening, and the n values in the Herschel-Bulkley model increase with the maximum grain diameter.

A linear increase of the shear stress with the shear rate (i.e. n=1) as assumed in the Bingham model, is only observed at shear rates higher than 10–20 s^{-1}, which are larger than the shear rates more typical for debris flows. For the Rossiga event, shear rates of 1–2 s^{-1} were estimated as the ratio between the maximum velocity and flow depth measured in the field (PHILLIPS & DAVIES, 1991; IVERSON, 1997), whereas values of 1-5 s-1 result from the numerical model. This discrepancy affects the relevance of the values assumed by the coefficient relative to the viscosity. These values are very sensitive to the shear rate interval considered for their calculation and they can be either underestimated or overestimated in case of shear thickening or shear thinning behaviour, respectively. The type of

shear rate behaviour depends on the material composition, being thinning for fine grained, cohesive material (i.e. mudflows) and thickening for coarse – grained, frictional and collisional material (i.e. granular flows). The condition of constant viscosity (i.e. n=1) assumed in the Bingham model is only a restricted, transitory condition in between the more frequent shear thinning and shear thickening behaviours.

The rheological parameters varies largely among the tested samples (figure 7), confirming that the flow behaviour may change during the same event from the source area to the deposition zone according to any variation in the material constituents. The yield strength, in particular, varies markedly with the material composition. The largest values are observed for the samples composed by material finer than 0.075 mm alone. In this case the yield strength is provided by cohesion and its magnitude (at the solid concentrations considered in the analyses) is compatible with the value observed in the field. Adding larger sized particles first reduces and then increases the yield strength (table 3; Sosio and Crosta, 2009).

The variations resulting from changing the material composition and origin are marked and are out of the range of variability of the back calculated parameters (figure 7 a). The viscosity values resulting from direct measurements, on the other hand, vary within the range of uncertainty of the back calculated parameters (figure 7 b).

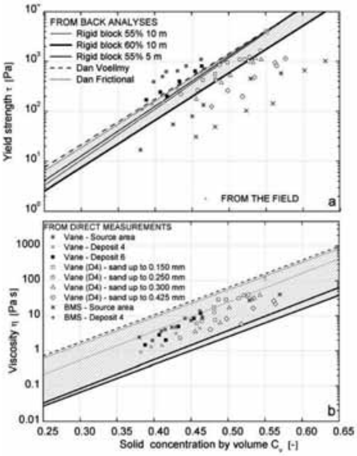

Fig. 7 - Trends of the viscosity and yield strength with sediment concentration determined by each analysis, for the different scenarios. Estimation of the rheological parameters assessed in the field are reported. The viscosity values obtained by the rheological analysis (a) fall into the range of uncertainties of the model while the yield strength values (b) are up to one order of magnitude lower than the back-calculated ones

CONCLUDING REMARKS

We propose different alternative choices for assessing unavailable or uncertain data (i.e. inflow hydrographs, rheological parameters), and we compare models at different topographical resolution to evaluate which assumptions better approximate the debris flow event and which input data are more critical for the modelling within the alternative consider.

The Rossiga event is best replicated assuming the initial motion of the landslide as frictional and Voellmy (Scenarios Dan-F and Dan-V) with slight variation among each other, either considering the flow and deposit thicknesses and the values resulting from the back analyses of the rheological parameters.

Changing the initial conditions (i.e. initial inflow, rheological description) determines large variations in the modelling results. To replicate the event evidences, the viscosity values have to be adjusted by more than one order of magnitude among the scenarios. The back-analysed yield strength, which controls the deposit thickness, accomplishes more narrow variations. On the other hand, the values of the rheological parameters determined by direct measurements fall within the range of possible values defined by the back analyses, so that the uncertainty related to the inflow hydrograph remain the most critical.

The use of the vane geometry is suggested against those of the Ball Measuring System (Schatzmann *et alii.*, 2003). The vane cell geometry reduces some experimental problems (e.g., slip at the wall, evaporation, and extrusion of the sample), which commonly occur when testing concentrated suspensions (Coussot *et alii.*, 1993; Barnes & Nguyen, 2001) and ensures an higher homogeneity of the sample. This results in an higher reproducibility of the measurements (±12%) in a wider range of shear rates and testing conditions. Adopting the vane geometry (minimum gap between the vane blades and the shear cell of 3.5 mm), a maximum grain size dimension of 0.300 is suggested for avoiding perturbing effects (i.e. end effects, lack of homogeneity within the suspension) during measurements (Sosio & Crosta, 2009). The measures obtained on the suspensions with 0.300 mm are in agreement with the field estimations and produces good results when adopted for replicating the Rossiga debris flow event (figure 5).

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