TORRENTIAL HAZARD ASSESSMENT USING A DEBRIS-FLOW RUNOUT MODEL. THE CASE OF THE FAUCON STREAM.

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ABSTRACT: Debris-flows are able to transport large quantities of sediment downslope, producing complex distributions of deposits and eroded surfaces along their flow path. Incorporation of surficial deposits during a debris-flow may change the mechanical behaviour of the flow. This paper presents the results of various rheological tests and numerical modelling for assessing torrential risk scenarios in the Faucon torrential stream where a debris-flow occurred in 1996, after a severe thunderstorm over the catchment basin and the breaking of a natural dam. Grain-size distribution and petrographic analysis have shown that this debris-flow can be characterized as a granular then a muddy debris-flow. Rheological tests using either a parallel-plate rheometer, a coaxial rheometer, slump tests, or a inclined plane were carried out on several samples. Results have shown that the flow behaviour could be described by a Heschel-Bulkley constitutive equation. Rheological response of several natural suspensions collected from quaternary deposits were also investigated. In order to model the runout of the flow, we used the BING code. Model describes well the influence of each type of sediment on the behaviour (runout distance, deposit thickness) of the flow, neither the velocities were overestimated. Different risk scenarios are tested and discussed.

Keywords: debris-flow, rheology, herschel-bulkley, numerical modelling, hazard assessment

1 INTRODUCTION

In torrential streams, intense and localised storm may trigger sediment transport like hyperconcentrated flows or debris-flows. Debris-flows usually move downvalley in a series of surges with steep fronts that consist mostly of large boulders. The triggering mechanisms (Johnson, Rodine 1984, Johnson, Sitar 1990, Iverson et al. 1997, Wieczorek et al. 1997, Cojean, Staub 1998) and the behaviour of debris-flow (Major, Pierson 1992, Coussot, Meunier 1996, Coussot 1997) are well known, yet only few studies (Hungr et al. 1984, Scott 1988, Pierson et al. 1990, Fannin, Rollerson 1993, Jakob et al. 1997, Berti et al. 1999, Massimo 2000, Ghilardi et al. 2001) take into account the erosion/deposition process and the different behaviour of additional sediment in the mixture. Channel scouring during a debris-flow event can be responsible of high difference in sediment accumulation between the triggering area and the deposit area. Berti et al. (1999) noticed that only 10 percent of the total volume of a debris-flow event in the Dolomites were mobilized from the source area, the rest of the material were incorporated along the channel. Debris-flows progressively increase in volume along their flowpath by 10-50 times because of entrainment of loose material and bed scouring (Vandine, Bovis 2002). Moreover, in watershed characterized by various lithology, rheological response of the different surficial deposits will be variable. Furthermore, run-out characteristics of the debris-flow (velocity, discharge, spreading) evolve according to the rheological parameters of the surficial deposits incorporated in the flow by erosion process. The Faucon torrent, in the Barcelonnette basin, was selected as an experimental site because an important debris-flow occured in 1996 (Remaître et al. 2002a) and because the geomorphological and hydrological conditions of the area are quite typical of other torrents in the basin with an heterogeneous bedrock. A study has been carried out to:

- define the sedimentologic and the rheologic characteristics of the 1996 debris-flow;
- assess the rheological characteristics of each main surficial formations located in the Faucon watershed;
- model the runout of this debris-flow, assuming a Herschel-Bulkley flow type, and to calibrate models on the observed event;
- back-analyse the runout distance and deposit thickness given by the model for various rheology, volume and total solid fraction.

In this paper the debris-flow runout occured on August 19, 1996 was simulated with the BING code.

2 AREA DESCRIPTION

The Faucon catchment is located on the south-facing slope of the Barcelonnette basin (Alpes-de-Haute-Provence, France). The Ubaye river drains the Barcelonnette basin, which slopes up from 1100 to 3000 m altitude. The upper rock crest comprises two massive sheet thrusts (Parpaillon and Autapie). The Ubaye river has carved out 13 000 ha in the autochthonous black marl. A number of factors, including lithology, tectonics, climate and the evolving land use, have given rise to the development of 26 torrential streams and various slope movements. There have been some 150 debris-flows in the Barcelonnette basin since 1850 (Flageollet et al. 1999). In 1996 there was an important debris-flow in the Faucon stream (Fig. 1), a tributary of the Ubaye river. The Faucon, which drains a 10.5 km^2 basin to the South, joins the Ubaye upstream of the developed area on the fan at 1170 m a.s.l. Local slopes are steeper than 25°, reaching 80° on the highest stretches in the headwater basin. Bedrock geology of the upper part of the basin is characterized by the two sheet thrust made up of limestones, sandstones and flyschs. Black marl dominate the basin. Apart from the channel and its side slope, the basin is covered by quaternary deposits, varying in thickness between 3 and 15 m. Quaternary deposits, mostly consisting of moraines, screes and landslides accumulations are susceptible to landsliding because of their steepness. They can become saturated during extended periods of high precipitations. The Faucon torrent has formed a huge debris-fan (Fig. 1a) that spreads across the Ubaye valley floor. The torrential fan extends southward for about 1 km and covers an area of 2 km^2 ; it has a slope ranging from 6 to 9°. Since 1850, a dozen debris-flow occured in the Faucon stream (one event each 10 years). 76 check dams were built during the 1890s to prevent flooding but only a half of them is still efficient.

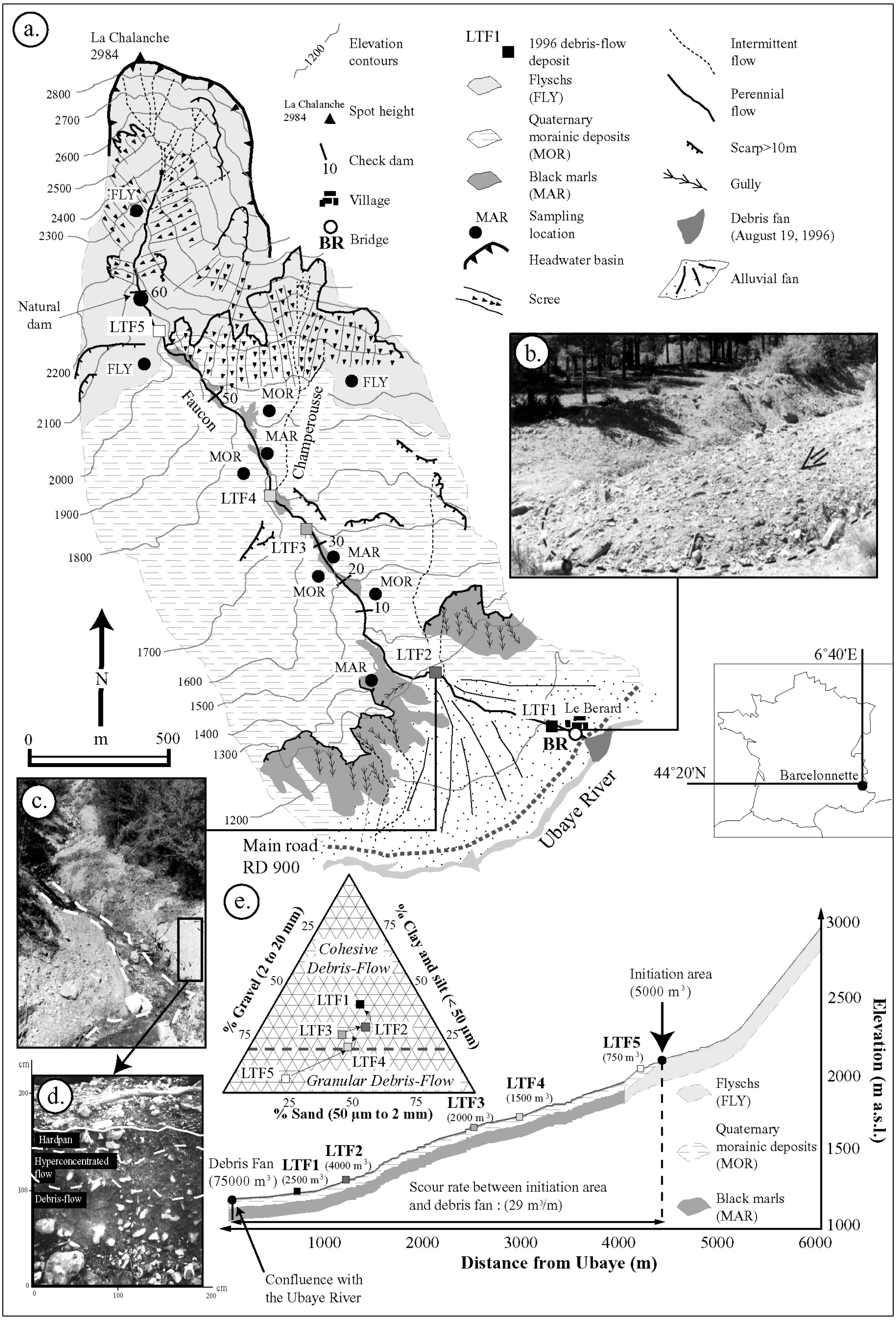

Figure 1. General presentation of the Faucon watershed and the 1996 debris-flow. Morphological map of the Faucon watershed (1a). Photographs of the LTF1 deposit (1b). Photographs of the LTF2 deposit (1c). Section of the LTF2 deposit (1d). Path profile of the Faucon stream and location and texture of the five 1996 debris-flow samples (1e).

3 THE 19th AUGUST 1996 EVENT

On August 19, 1996 a debris-flow was triggered by an intense and localised thunderstorm. The breaking of a natural dam (2100 m a.s.l.) after the concentration of loose material in the stream caused a debris-flow (Fig. 1a). The estimated volume of the material mobilised in the source area was approximately 5000 m^3. Downstream, due to the passage of the flow, severe channel bed souring was caused, increasing the volume of the debris-flow. Erosion and incorporation of the material was particulary severe in the black marls outcrop (1900 to 1300 m a.s.l.). Lateral and channel bed deposition occured downstream from 1500 to 1200 m a.s.l. They form discontinuous narrow ridges rising 2-3 m above the surrounding slope on both sides of the channel (Fig. 1c). Length of the levees can reach more than 100 m for 30 m wide. Lobe debris deposits were about 150 m wide and 200 m long on a slope ranging from 8 to 12° with an average thickness of 1.5 m (Fig. 1b). Surface material presents various sizes and shapes. Lateral sorting of the debris-flow deposit is poor, whilst vertical rough sorting is high. The coarser clasts and the boulders are concentrated at the top of the flow surface, producing inverse grading, as observed by many authors (Costa 1984, Takahashi 1991, Major 1998, Berti et al. 1999, Hungr et al. 2001). The total volume of the debris deposit was estimated to be approximately 100 000 m^3. Channel scour is responsible for the difference in sediment accumulation between the 5000 m^3 of the breached dam and the 100 000 m^3 of sediment deposited. Channel scour (S) per meter channel length was estimated according to the empiric formula proposed by Jakob et al (2000):

$$S = (V_{tot} - V_{ini}) / L_c$$

Where V_{tot} is the debris volume of the deposited material, V_{ini} is the volume of the debris-flow initiation area and L_c is the channel length from the fan apex to the breached dam. With V (tot) = 100000 m^3, V (ini) = 5000 m^3, and L(c) = 3300, the scour above the fan apex amounts to 29 m^3 metre channel length (Fig. 1e). The velocities (approximately 5 $m.s^{-1}$) were back-calculated using the forced vortex equation (Johnson, Rodine 1984) and multiplied by the cross-sectionnal area to obtain peak discharge estimated that ranged from 90 $m^3.s^{-1}$ to 110 $m^3.s^{-1}$.

4 LABORATORY TESTS

Our study of the initiation and the scour phenomena of debris-flows includes a sedimentologic analyses of the surficial deposits and the debris-flow deposits, and a rheological investigation. Five samples of the 19th August 1996 debris-flow were analysed (LTF), the three main surficial deposits (weathered black marls (MAR), weathered flyschs (FLY) and moraines (MOR)) were either described and analysed (Fig. 1a).

4.1 *Debris-flow deposits*

Five debris-flow deposits were sampled (Fig. 1a and 1e), two in the lower part of the stream near the apex (LTF1, 1270m a.s.l.) and on the debris fan (LTF2, 1200m a.s.l), two in the central part of the stream (LTF3, 1620m a.s.l. and LTF4, 1715m a.s.l.) in the black marls outcrop environment, and in the source area located in the sheet trust (FLY) outcrop (2050m a.s.l.).

The grain-size distribution, obtained on the fraction passing 20 mm sieve, shows a remarkable difference between the 5 samples (Fig. 2a). The choice of < 20 mm for the grain size distribution characteristics of the material was dictated by practical considerations and used by many authors (Bonnet-Staub 1998, Berti et al 1999, Hübl , Steinwendtner 2000); it represents 55-80% of the weight of the total grain size distribution. The percentage of fine elements (finer than 0.050 mm) did not exceed 7% for LTF5 (source area), whilst it is 30% in the LTF1 deposit. This fines enrichment is essentially due to the passage of the flow on the loose formations (MOR and MAR) of the intermediate reach of the channel. According to the classification of Staub (1998), LTF5 is classified as a granular debris-flow, whilst LTF1, LTF2, LTF3 and LTF4 are classified as a muddy debris-flow. Atterberg limits (Fig. 2d) classify the deposited material as inorganic silt with low plasticity (IP equals 7-8%) and a liquid limit of about 25%. Grain-size analysis (Fig. 2b) and petrographic analyses show that the three surficial deposits (MAR, FLY and MOR) bulked the debris-flows (Remaître et al. 2002, Remaître et al., in press).

Rheological parameters (yield stress, viscosity) of the debris-flow have been investigated using several methods (rheometrical tests, slumps tests, inclined plane tests) to have a good representation of the grain size distribution. Complete methodology has been explained in Malet et al. (in press). Several physical explanations for viscoplastic behaviour have been suggested; the behaviour of debris-flow is usually described using empirical models. Three models were tested (Bingham, bi-linear and Herschel-Bulkley) for all the materials and for the various solid volume concentrations. The validity of the results has been discussed; it should be noted that rheological parameters obtained with the two rheometric geometrical forms (parallel-plate, cone-plate) are close for estimating the yield stress (R^2 = 0.98) (Malet et al. 2002). Considering that our debris-flow fluids are slightly thixotropic and the shear rate used is sufficient low, the yield stress (τ_c) fitted by models is close to the real yield stress (Coussot, Piau 1994). For all the shear rate, LTF tends to a visco-plastic behaviour, well fitted by an Herschel-Bulkley constitutive equation (R^2 = 0.85). Herschel-Bulkley parameters (τ_c, K) are decreasing with the volume concentration, n varies between 0.17 and 0.40. The yield stress ranges from 1 to 117 Pa, viscosity from 1 to 72 Pa.s. The estimation of yield stress by rheometry, slump test and inclined channel gave more dispersed results . Relative error varied between –20% and +20% (Malet et al., in press).

4.2 *Surficial deposits of the Faucon watershed*

Several samples (about 10 for each type of surficial deposits) of the three types of surficial deposits were analysed. Grain-size distribution obtained on the fraction passing the 20 mm sieve, distinguished well the three formations: weathered flyschs (FLY) are sandy gravels, weathered black marls (MAR) are sandy clay and morainic deposits (MOR) are sandy silts. The three materials present approximately the same mineralogy (composed by illite, chlorite and kaolinite), furthermore they present no thixotropic behaviour (Malet et al. 2002). Rheological characteristics, estimated with the three methods, of the main surficial deposits have to be put in relation with the grain-size distribution, indeed FLY provides the weakest yield stress (2-30 Pa) while MAR provides the highest (14-800 Pa).

5 NUMERICAL MODELLING

5.1 *Model characteristics and objectivs*

For the debris-flow runout analysis the one-dimension flow-dynamics model Bing, developed by Imran et al. (2001) for the study of the downslope spreading of finite-source debris-flow, has been used. The model is based on the numerical model of Jiang and LeBlond (1993). The numerical model solves conservation of mass and momentum equations that are integrated over the viscous and the plug layer thickness and then expressed in a Lagrangian framework. The number of grid cells remains the same throughout the calculation. Starting from an initial parabolic shape the debris mass is allowed to stretch until the front velocity decelerates to a negligible value at which point the calculation is terminated. The model enforces a no-slip bed condition and erosion, deposition, and entrainment of water and sediment are neglected (Marr et al 2002, Imran, 2001).The

BING code has been used either for the study of submarine fast slope movements (Marr et al 2002) than for subaerial debris-flow (Malet et al (submitted)). The model incorporates various rheological models (Bingham, Herschel-Bulkley, bilinear -Locat, 1997-) of viscoplastic fluid. For these simulations, the most widely used Herschel-Bulkey rheology (Coussot, 1997) was considered. In the Herschel-Bulkley rheology, the mud is considered to consist of a distinct shear layer and a plug layer. The shear stress at the interface of these two layers is the yield stress. Starting from an initial parabolic shape, the debris mass of viscoplastic mud is allowed to collapse and propagate on a given rigid impermeable slope. The number of grid cells remains the same throughout the calculation. Each grid note is allowed to move at the local depth-averaged velocity after each time step. As a result neighbouring nodes can move closer or away from each other (Imran et al. 2001). The output results are not sensitive to the number of nodes. Indeed variation of the deposits depth and the velocities ranged between 0.5 and 2% for a number of nodes ranging between 10 and 100 nodes. We decided to use 20 nodes for reducing the time of computation.

The objectivs of the numerical modelling are:

- to check the validity of the model by comparing output results and field observations;
- to define the minimal volume of the source area necessary to reach the apex and the confluence with the Ubaye River;
- to evaluate the influence of each parameters (volume of the source area, yield stress, density) on the deposit thickness.

Determination of the values of the input parameters for the model are made from previous work on the study area (Remaître et al 2002, Malet et al 2002, Remaître et al (submitted)). Longitudinal path profile obtained from GPS survey and a careful morphological mapping is used in the model simulation. It is important to notice that check dams have been included in the path profile. The slope on the Faucon stream ranges from 80° in the headwater basin to 2° on the fan.

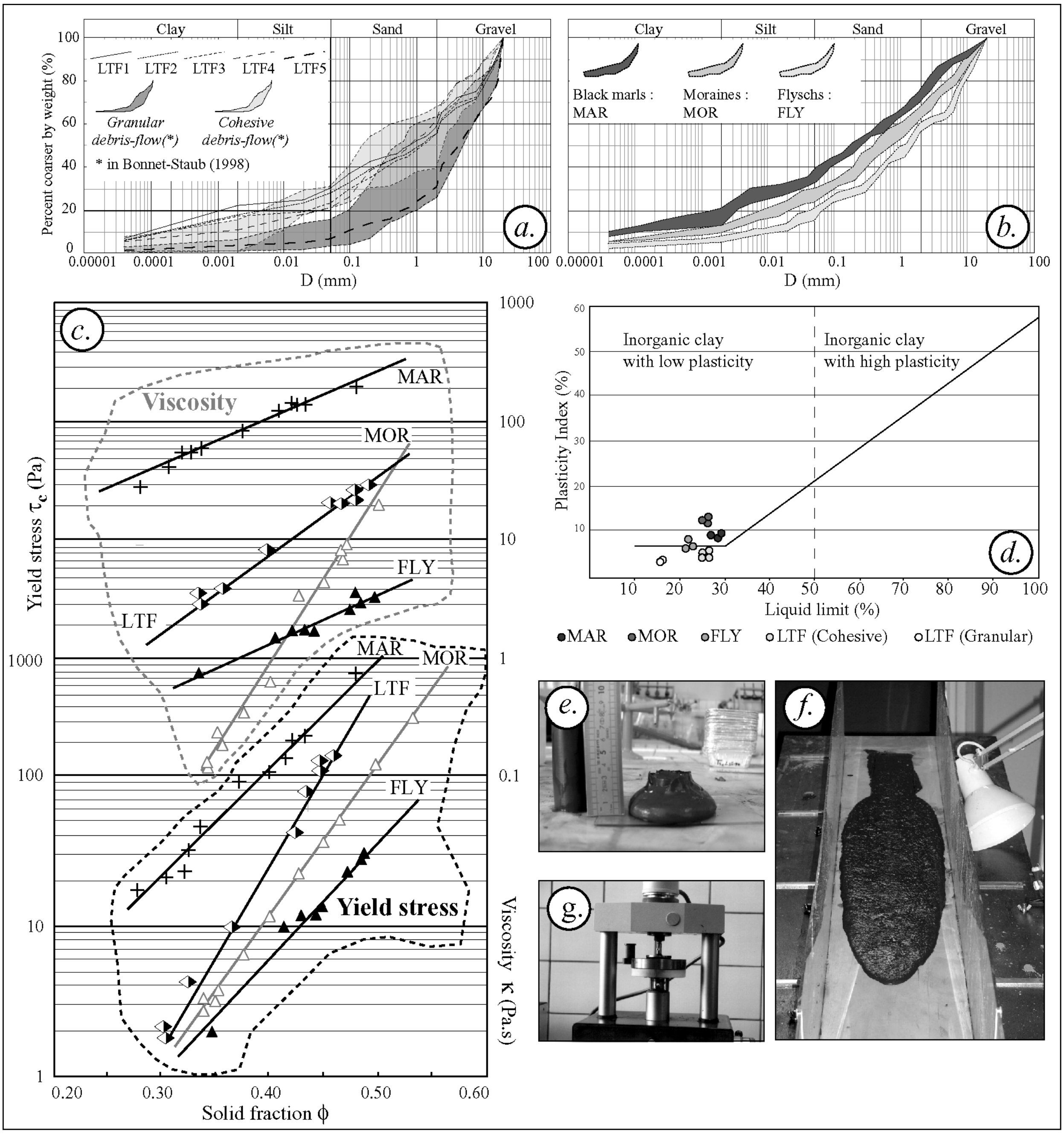

Figure2. Grain-size distribution of the LTF deposits (2a) and of the three main surficial deposits in the Faucon watershed (2b). Rheological characteristics (yield stress and dynamic viscosity) (2c) and Atterberg limits (2d) of the LTF deposits and the three main surficial deposits. Photographs of the three rheological tests, slump test (2e), inclined plane (2f) and parallel-plate rheometer (2g).

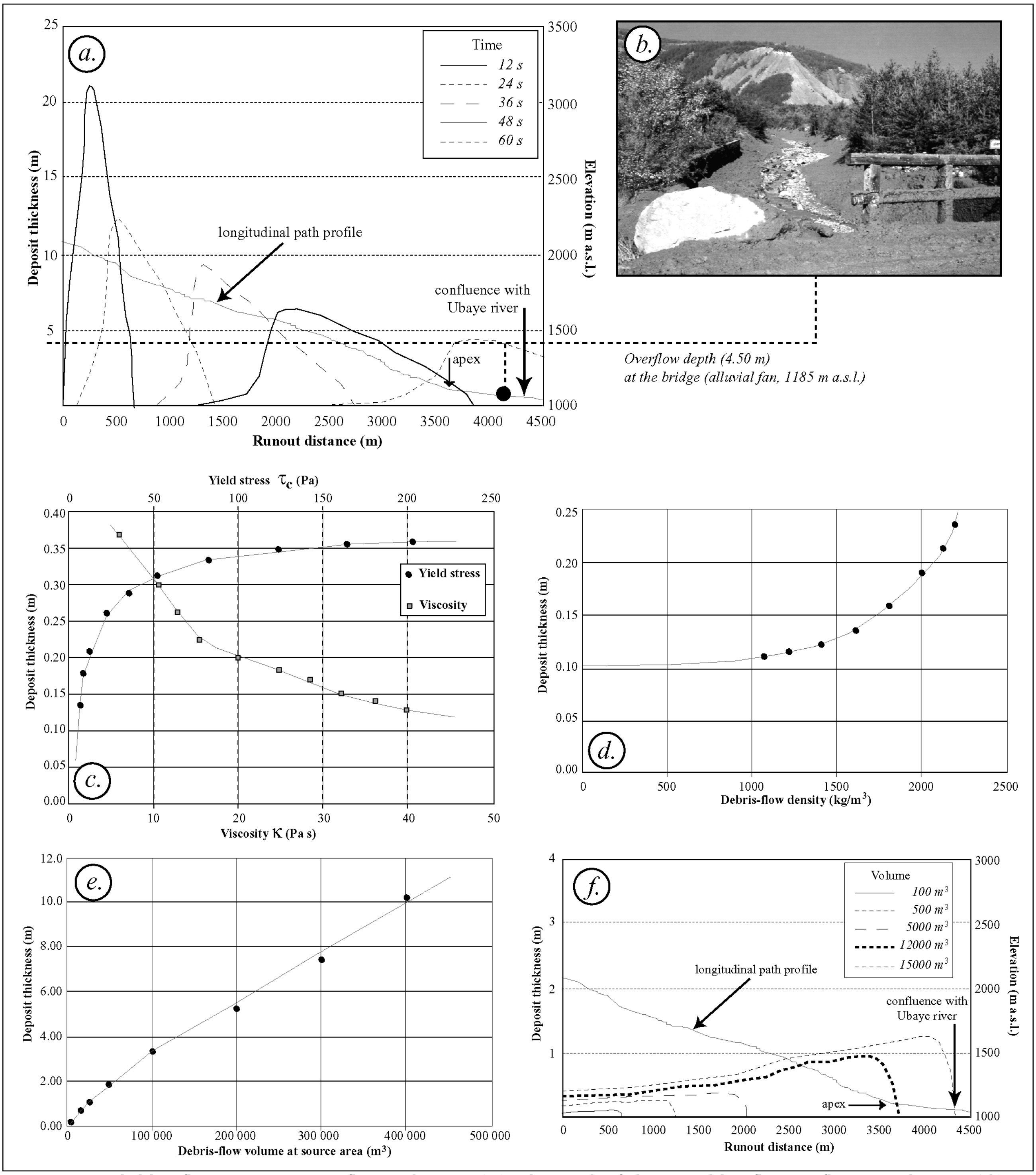

Figure 3. Computed debris-flow geometry to overflow at the apex (3a). Photograph of the 1996 debris-flow overflowing at the apex (3b). Parametric study with the BING code (3c, 3d and 3e). Runout distances calculated with the BING code for various debris source volume (3f).

5.2 *Calibration of the BING code*

First step consists to check the validity of the model. Field observations (deposit thickness, velocities) and laboratory tests (yield stress, viscosity) were compared with the outputs of the BING code. A back-analysis of the mobility of the 1996 debris-flow was carried out (Fig. 3a). Runout distance at stoppage could not be used, indeed the 1996 debris-flow reached the Ubaye river. Input parameters are given in table 1. A careful geomorphologic survey and field observations have shown that the 1996 debris-flow maximum flow depth, with a thickness of about 4.5 m, occured immediatly upstream of the bridges on the alluvial fan (Figure 3b), indicates as BR in Figure 1a.

Table 1. Input parameters used in BING simulations

Bulk density (kg/m^3)	Yield stress (Pa)	Viscosity (Pa s)	Length of deposit (km)	Thickness of deposit (m)
1600 - 2000	30 – 1000	5 - 100	0.01 - 0.5	10 – 200

The best-fit deposit thickness is obtained for yield stress and source area volume ranging respectively from 110 to 150 Pa and 110 000 to 125 000 m^3. Comparisons between the computed output and the field observations are given in table2 .

Table 2. Comparisons between field observations and numerical simulations

	Field observations and laboratory tests	BING input
Yield stress (Pa)	90 - 120 (*)	110 - 150
Viscosity (Pa s)	5 - 40	15 - 60
Total volume (m^3)	75 000 - 150 000	110 000 – 125 000
	Field observations and laboratory tests	BING ouput
Deposit thickness (m)	4.60 (**)	4.50
Velocities ($m.s^{-1}$)	4.9 – 5.1	20 - 70

* for a total solid fraction (ϕ) ranging from 40 to 50 ;
** observed at a bridge located on the alluvial fan.

These results check that the Herschel-Bulkley constitutive equation and the BING code are able to replicate, for various total solid fractions and rheology, field observations. The only problem consists in the high overestimation of the debris-flow velocity by the BING code. Indeed as shown by Malet et al (in press) the velocities are three orders of magnitude higher than that measured in the field. This is mainly due to an underestimation of the real viscosity mobilised during shearing, which must be three orders of magnitude more. A flow velocity of 5 $m.s^{-1}$ is given by BING for a viscosity of 250 Pa s and a yield stress of 7500 Pa.

In order to evaluate the influence of each input in the given deposit thickness, a parametric study has been undertaken. For the same initial conditions, different tests have been provided for various input parameters (Yield stress, viscosity, volume of sourse area, bulk density). Results show a strong relation between the volume of the source area and the deposit thickness (Figure 3b). The other parameters seems not to have a strong influence on the deposit thickness (Figure 3a, 3c). The yield stress for example only strongly influences the velocities and the shape of the deposit at stoppage.

5.3 *Debris-flow hazard scenario*

Assessment of debris-flow hazards on alluvial fan is essential for the risk management in moutainous area, especially for debris-flows, which can move huge volumes of sediments. These areas are periodically exposed to catastrophic events, this is particullary the case in the Ubaye valley (Flageollet et al 1999, Malet et al 2002, Remaître et al 2002, Remaître et al. in press). To reduce debris-flow hazard, it is common to couple structural and non structural protections, such as zoning of the risk prone areas. Protection plans require the definition of scenarios that can be assessed by means of simulations with numerical models. In our case, we estimate the potential volume of debris to reach the apex and/or the confluence of the Ubaye river.

Several numerical simulations were performed, using the best-fit parameters from the 1996 debris-flow mobility analysis, by changing the volume of released debris for various various yield stress (we used yield stress obtained on MAR, FLY, MOR and LTF samples). Results show a strong relation between the runout distance and the volume of the source area, indeed the runout distance increases with the volume. Figure 4 shows that the debris-flow volume must be at least more than 12 000 m^3 for reaching the apex and 13 500 m^3 for reaching the confluence with the Ubaye river. We can notice than in 1996 the debris source volume was approximately 5000 m^3, so if any scouring phenomena has occured, the debris-flow would not have reached the confluence with the Ubaye River. We can suppose that small failure volume required an additional mechanism to generate long runout distances. Runout distances differences between the four types of material must be put in relation with their rheological characteristics. The material with the weakest yield stress (in our case FLY) presents the highest runout distance, but not the highest thickness deposit. So increases in yield stress (by addition of an surficial deposit in the mixture by scouring) result in shorter runout distances and thicker final deposits. Additional data must be obtained for artificial mixture of this three main surficial deposit to find the mixture which presents the more favourable characteristics for flowing (weakest yield stress).

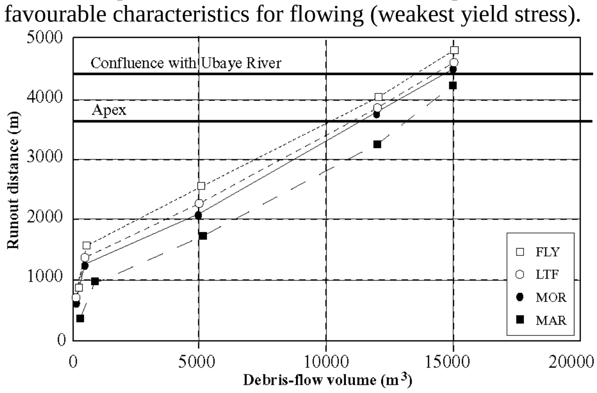

Figure 4. Estimation of the debris volume necessary to reach the apex of the torrent and the Ubaye river confluence for LTF, FLY, MOR and MAR (for ϕ = 0.45).

6. CONCLUSION

A combination of several analyses (geomorphological survey, sedimentological analyses, rheological tests, and numerical modelling) provides valuable data on the 1996 debris-flow event. Comparison of the 1996 debris-flow deposits with the three main surficial deposits has helped us to understand triggering conditions and scouring phenomena during this event. Grain-size distribution and petrographic analysis of the debris-flow deposit bring out the granular character of the flow during the first hectometer and its muddy character beyond that point and as far as the debris fan. Geomorphic observations and laboratory tests show the existence of two source areas: a triggering area and several contributing areas. These contributing areas, characterized by the presence of black marl outcrops and a morainic cover, seem to have supplied the bulk of the flow material. Field observations and laboratory tests were introduced in the BING code in order to model the runout of the 1996 debris-flow. In order to check the validity of the code, comparisons of BING computation output datas and runout characteristics measured on the field have been carried out. Results show that the Herschel-Bulkley constitutive equation and the BING code are able to replicate, for various total solid fractions and rheology, field observations. Parametric sutdy with the BING code revealed that several parameters influence final deposit runout and thickness, especially debris source volume and rheometrical characteristics (yield stress). At least, additional computation with several type of source material show that the debris-flow volume must be at least more than 13 500 m^3 for reaching the confluence with the Ubaye river. The rheological parameters of the sediment of the source area seems to influence debris-flow runout distances and deposit thickness. Nevertheless, development of better tools for modelling debris-flow with high scouring potential is required, especially for debris-flows triggered in heterogeneous watershed.

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