Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Rickenmann & Chen (eds)

Flow susceptibility of heterogeneous marly formations: implications for torrent hazard control in the Barcelonnette Basin (Alpes-de-Haute-Provence, France)

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ABSTRACT: Earthflows, debris avalanches and debris flows occurring in black marls in Southeast France present differentiated morphological characteristics and velocities. The rheological response of these remoulded fine-grained flow-like landslide deposits have been investigated using several techniques (parallel-plate rheometry, coaxial rheometry, slump tests and inclined plane tests). This contribution shows that rheological characteristics can be useful in establishing the transformation process of the materials into flow-like phenomena and identifying the natural mixture of basic formations which present the weakest yield stress and viscosity. Results show that the simple shear behaviour of all these natural flows clearly distinguishes the type of movement, in particular for earthflow and debris flow. Furthermore, some proportion mixtures present the highest mobility properties, and thus the highest susceptibility for transformation into high-speed flow-like phenomena. Results may be useful for identifying potential source zones in muddy flow-like landslide prone areas.

1 INTRODUCTION

Fine-grained gravitational movements presenting flow characteristics are frequent on the slopes or in the channels of torrential basins comprising black marls in Southeastern France. According to eyewitness observations and on the basis of Hungr et al.'s classification (2001), three types of flow-like landslides occur in black marls: continuously slow-moving muddy earthflows (approx. 0.01 $mday^{-1}$), fast-moving muddy debris avalanches (0.5-1 $mmin^{-1}$) and fast-moving muddy debris flows (5 ms^{-1}). Moreover, earthflows, debris avalanches and debris flows can be differentiated by the morphology of the deposits, the grain-size distribution and the geomechanical parameters. Earthflows are slower, gentler and cover short distances, while debris avalanches and debris flows are faster and cover long distances. All types of flows carry gravel and boulders up to 4 m in diameter, with more or less 60-70% mud (fraction <20 mm). The percentage of mud decreases from earthflows to debris flows.

According to Coussot & Meunier's (1996) rheological classification, the three flows may be thought of as three members within a continuum between "muddy solid" and "muddy fluids". Earthflows exhibit a behavior at the interface of "muddy solid" and "muddy fluid" near the "fracture limit" (Fig. 1). Nevertheless the behaviour can be well represented by viscoplastic empirical models (Ancey 2001). Debris avalanches and debris flows can also be represented in this way, as they are sufficiently concentrated. They behave as "muddy fluids".

Maquaire et al. (in press) have demonstrated a genetic link between these movements. On a short-term scale it is possible that the earthflows transform into debris avalanches or debris flows as they reached higher slope gradients in conjunction with having a higher proportion of sand and silt in their muddy matrix (Malet et al. in press). The transformation is governed by the progressive change in the granulometry of the materials, and by the addition of material (moraine, sandstone) other than the source material (marl). Similar transformation from fine-grained earthflows to muddy debris flows was reported by Colas & Locat (1993), Johnson (1997) or Couture & Evans (in press).

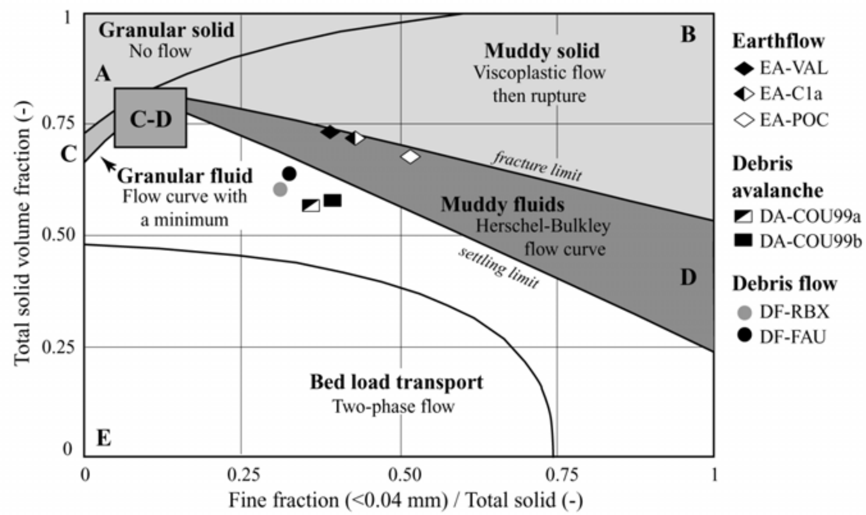

Figure 1. Position of the flow-like fine-grained landslides occurring in black marls in the conceptual rheological classification (function of fine content and total solid volume fraction) proposed by Coussot & Meunier (1996).

In the black marls outcrops of Southeastern France, earthflows, debris avalanches and debris flows involve marl, moraine and sandstone. A previous survey, grain-size distribution, consistency limits, and undrained cohesion have demonstrated that some mixtures of deposits present the highest mobility properties (Maquaire et al. in press), and thus the highest susceptibility to initiate high-speed flow-like phenomena. The direct determination of the behaviour of flow material with the help of rheometers is faced with the irretrievable problem that they generally contain particles of various sizes including big boulders (Coussot & Meunier 1996). Numerous studies have demonstrated that the behaviour of fine-grained flows is mainly guided by the muddy matrix, which acts as a lubricant, rather than the blocks or debris carried (Johnson 1965, Johnson & Rodine 1984, Pierson & Costa 1987, O'Brien & Julien 1988, Major & Pierson 1992, Coussot & Meunier 1996). At the opposite, in the case of coarse-grained flows where rheology evolves as mixture agitation, grain concentration, and fluid-pressure change during flow initiation, transit and deposition (Iverson 1997, Iverson & Vallance 2001), simple constitutive relations (Bingham, Herschel-Bulkley) are not able to capture the complex grain-grain and water-grain interactions controlling these flows. Grain-size distribution analyses of the flows show their muddy character (more than 60% of sand, silt and clay, and more than 25% of clay and silt). In such a case of fine-grained sediments, the presence of colloidal fractions may introduce yield stress (Hampton 1975, Major & Pierson 1992). We therefore carried out rheological measurements on the < 20 mm-fraction of the materials using parallel-plate rheometry, coaxial rheometry, slump tests and inclined plane tests.

The main objectives were to: (i) check if the differences in velocity, flowing mechanisms and other features of these muddy flows observed and measured in the field were in relation to the rheological characteristics of the muddy matrix; (ii) define how the material's grain-size distribution influences the mobility, and (iii) identify the mixtures (marl, moraine, sandstone) which present the weakest yield stress and viscosity. The paper presents the results of the rheological characterisation carried out on the deposits of various flow-like landslides and on artificial mixtures of marl, moraine and sandstone. The main hypothesis is the following: little differences in the grain-size distribution of the muddy matrix can strikingly change the rheological behaviour of the flows, and thus the velocities.

2 DESCRIPTION OF PHENOMENA AND MATERIAL

In the Barcelonnette basin (Alpes-de-Haute-Provence, France, Fig. 2), the materials tested were taken from deposits from three muddy earthflows (*Super-Sauze*, EA-C1a, EA-IND; *La Valette*, EA-VAL; *Poche*, EA-POC), two muddy debris avalanches which started on the upper part of the Super-Sauze earthflow (DA-COU99a, DA-COU99-b), two debris flows with a muddy matrix in the *Faucon* (DF-FAU) and *Riou-Bourdoux* (DF-RBX) torrents, weathered marls (Mar), moraines (Mor) and weathered sandstones (San). Eyewitness observations in the morphology of the deposits (streamlines, lobes, and bulges) and field measurements (Malet et al. in press) have shown that such flow-like landslides move predominantly by distributed flow, and exhibit distributed straining.

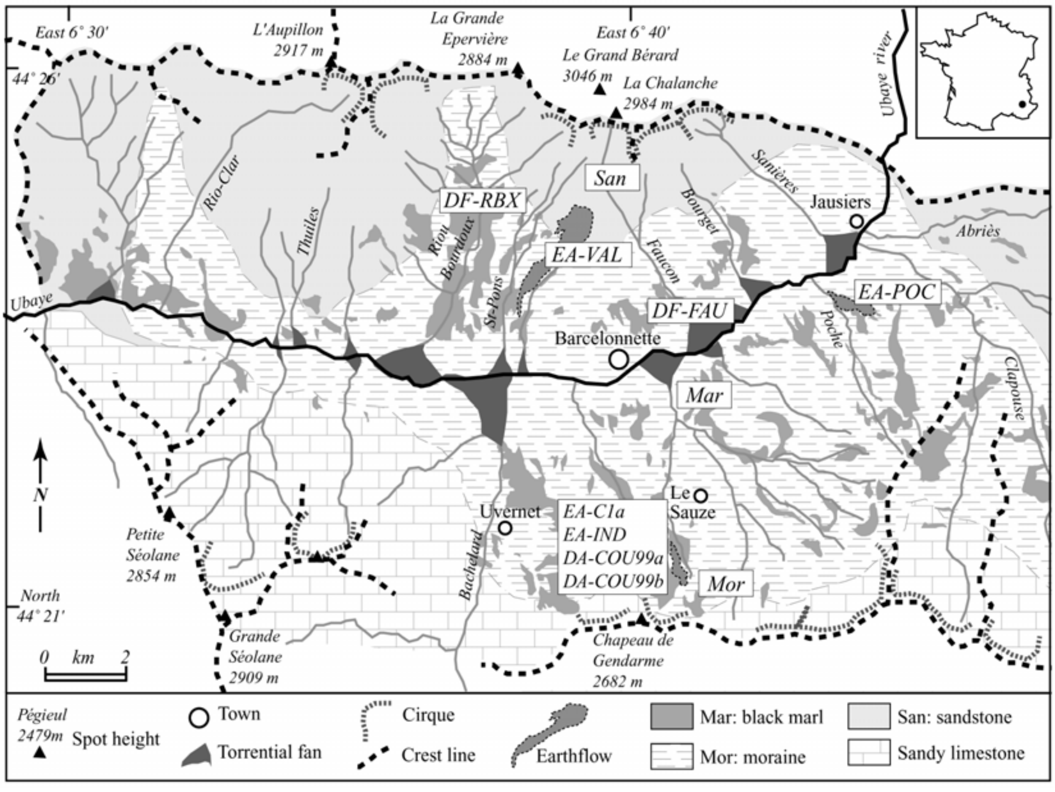

Figure 2. Morphological sketch of the Barcelonnette basin showing locations of the landslides deposits and extension of the landslide source material.

The earthflows exhibit a macro-viscous behaviour, with a wide range of velocity which varies with time. The channelized flow fossilizes a complex topography and creates accumulation lobes which may be as much as 20 meters thick, with no grading (Fig. 3a). Muddy earthflows involve the products of weathering of clay-rich rocks. Weathering produces a clayey colluvium with a consistency closer to the plastic than the liquid limit (Hungr et al. 2001). Field observations and measurements show that the movement may be maintained over long distances and for long periods of time by intermittent plastic deformations accompanied by built-up of interstitial pore water pressures. There are frequent sudden accelerations in the upper part of the flows above an interstitial pressure threshold. Muddy earthflows contain a maximum of 25-30% of coarse (gravel) material, though protruding boulders of up to 4 m in diameter can be coated in the mud. The accumulation lobes present fissures a meter in depth (Fig. 3a).

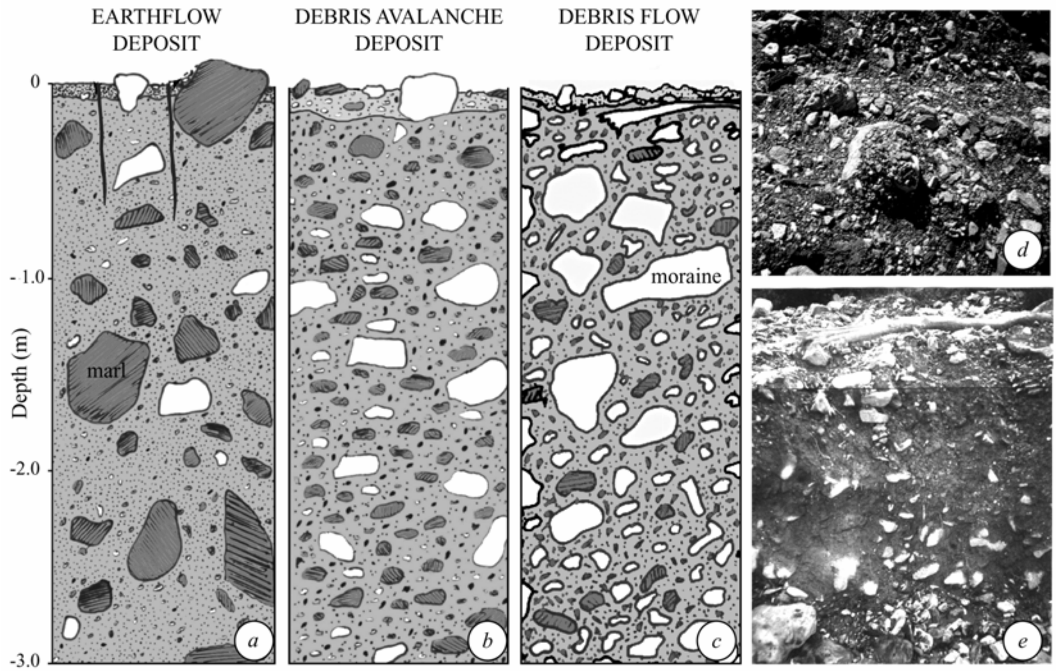

Figure 3. Morphological characteristics of the deposits. Schematic vertical stratigraphic sections of: (a) the EA-C1a earthflow deposit, (b) DA-COU99a debris avalanche deposit, and (c) DF-FAU debris flow deposit. Photographs of the stratigraphy at (d) the toe of the DA-COU99a debris avalanche and (e) DF-FAU debris flow.

At the opposite, the deposits of debris avalanches and debris flows are shallow (1-4 m thick), mainly flat-topped lobes, becoming progressively more sheet like in the downward direction. The debris avalanches deposits are mainly lateral levees or small accumulation cones showing no grading (Figs 3b, d). Debris avalanches observed in marls are rapid (0.5-1 $mmin^{-1}$), completely saturated and not channelized phenomena. The two debris avalanches observed in 1999 initiated as rotational slides but they acquired flow characteristics very quickly. The percentage of gravel is often between 30 to 35%. Most of the coarser elements are on the subsurface.

The debris flows are faster (5 ms^{-1}) than the debris avalanches and concentrate in torrential channels; two characteristics of debris flows are a deposit with inverse grading and lateral levees (Figs 3c, e). These lobes are flat, with convex sides. Lateral sorting is poor, whereas vertical rough sorting is high (Major 1998). The coarser clasts and boulders are concentrated at the top of the flow surface. The vertical section (Figs 3c, e) shows several successive beddings of varying granulometry: (i) an indurated stratum corresponding to the flow hardpan; this may be covered by a thin stratum of fine material deposited by a subsequent stream flow, (ii) an alluvial stratum or hyper-concentrated flow stratum, consisting of fine loose material with a high lateral sorting, and (iii) a debris flow stratum with coarser material and debris set in a fine matrix. The percentage of gravel is often comprised between 35 to 40%.

The grain-size distribution of the material and the plasticity domain are the factors which influence the differentiated response of materials to the movement. The comparison of geomechanical and rheological characteristics of the natural mixtures (earthflows, debris avalanches, debris flows) with those of the artificial mixtures comprising the three superficial formations in the Barcelonette Basin allows to: (i) identify the influence of each superficial formation in the behaviour of each flow-like landslide type, (ii) define the mixtures the most susceptible to mobility (weathered black marl, weathered sandstone, moraine). Two groups of materials were tested (Table 1): a combination of marl and moraine mainly found on the north-facing slope (EA-C1a, EA-IND, DA-COU99a, b, EA-POC, UM artificial mixtures) (Fig. 2) and the second combining marl, moraine and sandstone found only on the south-facing slope (EA-VAL, DF-RB, DF-FAU, AM artificial mixtures). The ponderal proportions are set out in Figure 4.

Table 1. Geomechanical characteristics of flow-like landslides and artificial mixtures.

	Grain-size							Consistency			Density
	Sand	Silt	Clay	Gravel	Q_{25}	Q_{50}	Q_{75}	W_P	W_L	I_P	ρ_{sat}
	%	%	%	%	mm	mm	mm				kg.m^{-3}
Landslides or in situ deposits											
EA-C1a	25	22	15	38	0.0170	0.600	10.0	16	32	16	2140
EA-IND	31	29	10	30	0.0023	0.400	2.50	17	33	16	1790
EA-VAL	32	20	11	37	0.0016	0.975	4.00	19	31	12	1730
EA-POC	20	42	9	29	0.0009	0.019	1.91	20	37	17	1830
DA-COU99a	35	24	9	32	0.0018	0.422	2.50	15	30	15	1700
DA-COU99b	27	30	10	33	0.0021	0.436	3.75	16	29	13	1670
DF-FAU	30	20	6	44	0.0190	0.800	8.30	19	26	7	1630
DF-RBX	36	16	10	38	0.0190	0.455	4.30	21	29	8	1650
Mor	38	12	9	41	0.0205	0.435	4.40	19	30	11	1590
San	37	11	5	47	0.0315	0.550	6.75	17	25	8	/
Mar	37	14	12	37	0.0220	0.400	4.20	21	29	8	1710
Artificial mixtures											
UM2	29	35	10	25	0.0015	0.270	2.45	18	31	13	/
UM3	30	29	9	32	0.0126	0.312	2.87	17	28	11	/
UM4	31	26	8	35	0.0208	0.421	3.19	16	26	10	/
AM1	31	17	7	45	0.0218	0.765	7.55	18	27	9	/
AM3	38	18	9	35	0.0156	0.603	6.14	21	33	12	/
AM5	40	12	7	41	0.0297	0.715	7.16	16	27	11	/
UM6	38	11	8	43	0.0302	0.726	7.08	18	28	10	/

All the materials are relatively homogeneous from a mineralogical standpoint, mainly comprising illites, chlorites and kaolinites. There is no swelling clay in these formations (Malet et al. 2002). The materials are characterized by their high percentage of gravel, increasing from the earthflow deposits (25-30%) to the debris flow deposits (35-40%). The gravel fraction is larger than the sandy fraction. Moreover, after some forty analyses on the fraction passing the 20-mm sieve, the three types of flow are clearly distinguished even though the granulometric characteristics of the samples are close. Muddy earthflow deposits contain an abundant fine-grained matrix with an essentially silty-clay texture, as muddy debris avalanche deposits have a silty-sand texture and debris flows deposits a sandy-silt texture (Table 1, Fig. 4). The earthflow deposits are rich in silt and clay (EA-C1a, EA-POC) as they consist mainly of weathering products of marl; the materials in the marl/moraine or marl/sandstone mixtures (EA-IND, EA-VAL) have more significant sandy fractions. In addition these values should be considered alongside the age of the earthflows; the older the earthflow the higher the percentage of clay and silt due to the weathering of the marls. The grain-size distribution of the debris avalanche is at the interface between earthflow and debris flow. Finally the DF-FAU and DF-RBX deposits are of the classic sandy-silt texture of debris flows with a muddy matrix.

The composition of the matrix allows distinction of the types of movement. This demonstrates a clear connection between the grain-size distribution composition and the type of flow and this result agrees with the flow classification based on the texture of the matrix suggested by Hungr et al. (2001). The debris flows contain less than 30% of silts and clays. These can therefore be distinguished from earthflows which are much more cohesive. The debris avalanches present an intermediate texture – this is a remarkable feature and should be noted. The artificial mixtures tested (marl, moraine and sandstone) represent the granulometric spectrum of the various phenomena (Fig. 4, Table 1). The percentage of fine material increases with the amount of marl in the mixture.

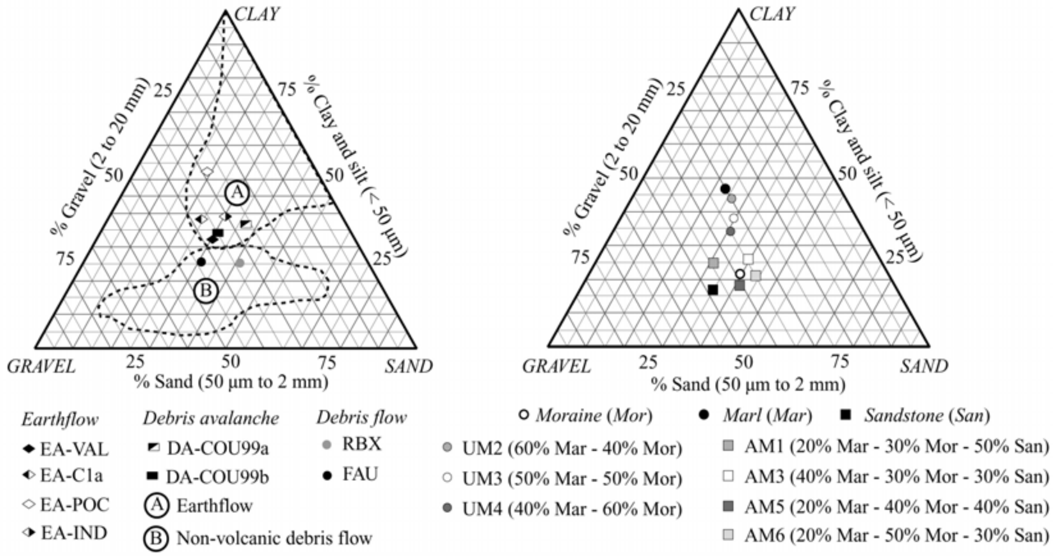

Figure 4. Textural composition of (a) landslide deposits and (b) artificial mixtures. Dotted lines represent the classification proposed by Hungr et al. (2001).

The Atterberg limits, and in particular the plasticity index (I_p), show a clear distinction between earthflow and debris avalanche (I_p=12–18) and debris flow (I_p=7–8), which exhibits very little plasticity. The liquidity limits, which are between 26% (DF-FAU) and 37% (EA-POC), guided our choice of total solid volume fraction for the rheological tests. It therefore emerges from these geomechanical characteristics that the more muddy and plastic the material the slower the flow velocities appear to be (for a similar slope gradient). The Atterberg limits for the artificial mixtures have low plasticity indices ($9<I_p<13$). The plasticity index varies positively with the increase of the proportion of marl, the least plastic mixtures being UM4, UM3, AM1, AM5 and AM6.

3 METHODOLOGY AND THE VALIDITY OF RESULTS

The rheological characterisation was conducted alongside rheometric tests (0–400 µm fraction), slump tests and inclined plane tests (0–20 mm fraction) in order to define the behaviour over a wide granulometric spectrum, taking account of the wide variety of total solid volume concentrations observed (Fig. 1).

3.1 *Rheometrical tests*

The fluids subjected to rheometric tests were suspensions of nine materials. The tests were carried out on six total solid volume fractions ϕ. A given volume of solid material was added to water and then mixed with a laboratory mixer to 600 t.min^{-1} for one minute and then to 400 t.min^{-1} for

30 minutes. The fluids were tested with a Rotovisco RV20 (Haake) rheometer equipped with rough parallel-plates (diameter, 50 mm; roughness, 250 μm; thickness of the sheared sample, 2.8 mm) and a Rotovisco RV12 (Haake) equipped with coaxial cylinders (MV-I sensor with a large gap: 0.96 mm). The experimental process, by imposed speed stages, and the precautions taken to limit the effects of disturbances (wall slip, edge effect, fracturing, particle migration, sedimentation) are described in detail in Magnin & Piau (1990). After a 30-minutes homogenisation period the fluid was introduced into the rheometer and sheared for two minutes at a shear rate of 1000 s^{-1}, then for 28 minutes at a rate of 100 s^{-1}. We used the experimental protocols described by Coussot & Piau (1994) for the parallel-plate geometry and by Locat & Demers (1988) for the coaxial cylinder geometry. The use of two geometries enabled us to investigate an extended range of shear rates. The protocols involve a succession of speed ramps (from 1.87 s^{-1} to 18700 s^{-1} for the parallel-plate rheometry and from 0.02 s^{-1} to 1200 s^{-1} for the coaxial rheometry) where each shear rate is maintained for a period of 15 seconds. The range of shear rates used in this study is 2 to 3 times higher than that met with this type of flow in the field (O'Brien 1986). Three viscoplastic empirical models (Bingham, bi-linear – Locat 1997 – and Herschel-Bulkley) were adjusted to the experimental data (Malet et al. 2002) for each material and each total solid volume fraction, taking account of the depth of the hollow observed in most of the experiment with the parallel-plate geometry (Coussot & Boyer 1995). The fluids are not thixotropic and the tests were carried out at sufficiently low shearing rates, so the yield stress τ_c should be well defined (Coussot & Piau 1994).

The shape and the range of the flow curves are similar in the range of shearing rates common to both rheometers. The Herschel-Bulkley parameters estimated from the two geometries are identical, in particular for the yield stress (Malet et al. 2002). The differences are in the margin of error specified by Coussot et al. (1996) which indicate that the difference in the shear stress measurements between one geometry and another is between 5 to 15 Pa.

3.2 *Slump tests*

The test comprises filling a cylinder (diameter, 42 mm; height, 82.5 mm) with the fluid (0–20 mm), raising the cylinder rapidly and allowing the material to sink under its own weight. The difference between the initial and the final height of the material and the thickness of the unsheared zone enables the estimation of the yield stress τ_c using the formula devised by Pashias et al. (1996). In addition to reproducibility, this test enables the characterization of material at higher solid fractions. Making allowances for uncertainties in rheometrical and slump test measurements the agreement between rheometrical data and slump tests results is very good. The "relative error" ($\Delta\tau_c/\tau_c$) fluctuates around a mean value which is close to 0.15, whatever the total solid volume fraction (Fig. 5a).

3.3 *Inclined plane tests*

We used a 4 m-long rectangular channel as an inclined plane; its width reached 0.25 m and its slope could be varied between 4 and 40°. The bottom surface was plywood. During the experiments we noticed that wall slip was negligible. The channel was equipped with a damming system upstream. The system was filled with 0.002 m^3 of material (fraction 0-20 mm) and then a bottom gate was opened quickly so that the fluid could flow downstream. In general the fluid appeared to flow slowly during a period of between 10 and 30 min. The asymptotic depth was measured far enough from the channel tips downstream and upstream for the fluid depth to correspond to the uniform depth. Yield stress was determined using the relation proposed by Coussot et al. (1996), taking into account the asymptotic flow depth and the shape of the lateral levee. Total solid volumes ranging between 0.35 and 0.50 were tested for each material.

The inclined plane tests results were quite reproducible: differences as low as 5% were recorded from one test to another. As for the slump tests, the "relative error" in the inclined plane tests results fluctuates around a mean value close to 0.15 (Fig. 5b).

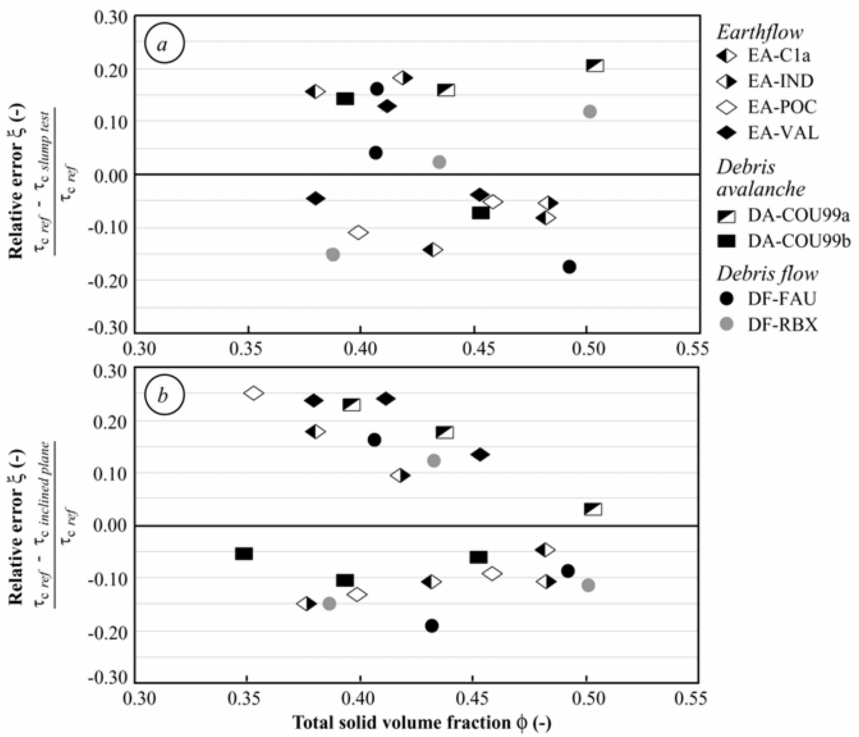

Figure 5. Error on yield stress determination using slump tests (a) and inclined plane test (b) as a function of solid fraction ϕ for each landslide deposits. The yield stress determined by the parallel-plate rheometry ($\tau_{c\ \mathrm{ref}}$) is taken as reference.

4 RESULTS

4.1 *Behaviour of flow-like landslide deposits (natural mixtures)*

All the materials present the same type of shear-thinning behaviour toward high shearing rates. Towards low shearing rates (typically between 0.05 and 1 s^{-1}), regardless of the total solid volume fraction, an inflection of the curve is observed for all materials from landslides, while material which has not moved (Mar, Mor, San) shows no inflection. The thixotropy of materials is low (Malet et al. 2002).

All the material presented a marked viscoplastic behaviour over the range of shear rates under consideration (Fig. 6a) and this is well represented by a Herschel-Bulkley model (determination coefficients greater than 0.85). All the materials indicate Herschel-Bulkley parameters (τ_c, κ) which increase with the solid volume concentration, with an exponent n between 0.25 and 0.40. The yield stress and the plastic viscosity varied respectively from 1 to 480 Pa and from 0.1 to 150 Pa. We observed a significant differentiation between the materials in the range of total solid volume concentrations ϕ from 0.35 to 0.50 while the materials present the same rheological parameters for high concentrations of water.

The master curves of the various materials were calculated in order to determine the rheological characteristics from simple field experiments (Fig. 6b). The shearing rates and the shear stresses were reduced by τ_c. In this way, in a graph ($\dot{\gamma} / \tau_c$, τ / τ_c), all the flow curves of a given deposit are adjusted on a master curve which tends towards a straight slope μ at high shearing rates and 1 at low shearing rates. In spite of the differences in grain-size distribution it is possible to represent the flow behaviour by a single master curve; the parameters of which depend only on the shear stress and the total solid volume concentrations. The master curve equations are given in Figure 6b.

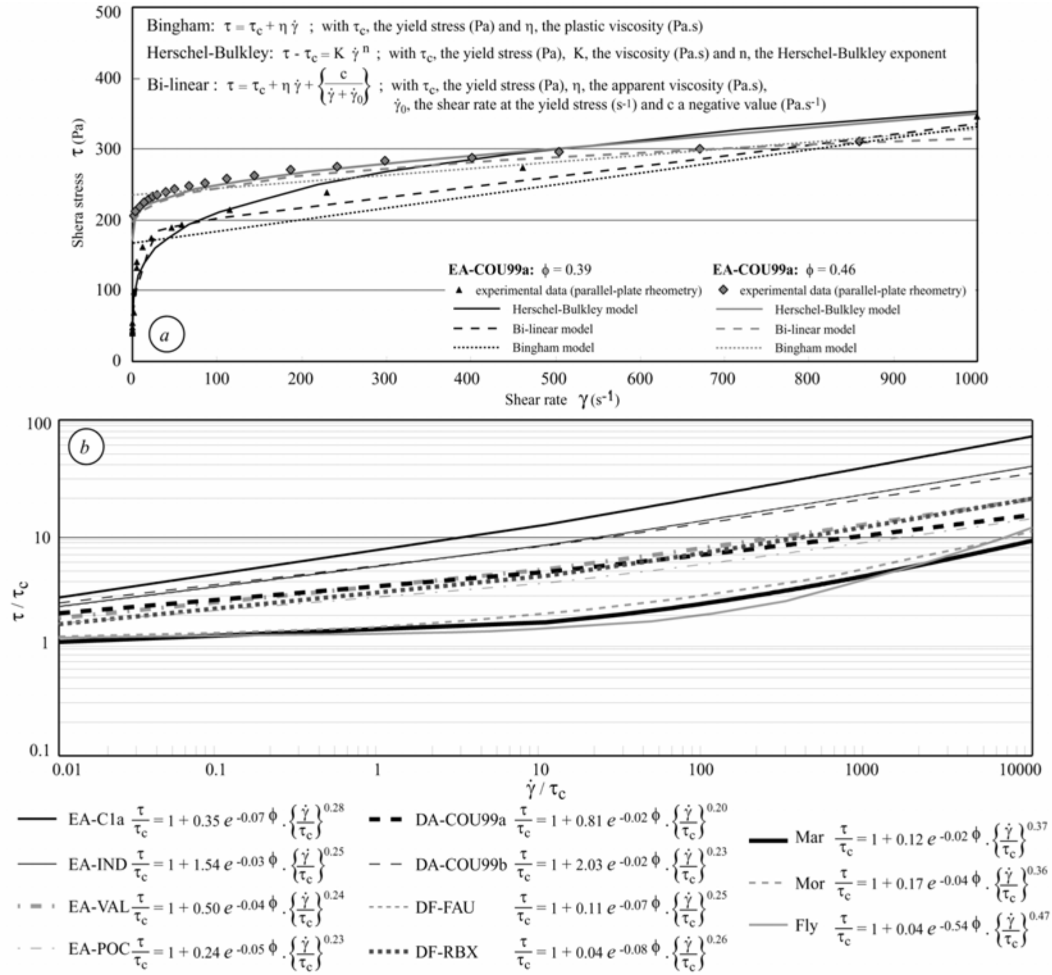

Figure 6. Fitting curve for the (a) COU99 material and (b) master curves of the landslides and *in situ* deposits.

The results of the rheological analyses reflect the variations in velocity observed in the field. It is interesting to note the similarity of EA-IND and DA-COU99a master curves, which show that the EA-IND material corresponds to the debris avalanche's source zone DA-COU99a. Only the superficial formations (weathered marl, sandstone, moraine) present a more marked bilinear behaviour, which can be explained by the fact that these formations have no history of flows.

4.2 *Behaviour of artificial mixtures and comparisons with natural materials*

The behaviour of all the artificial mixtures is also very well represented by a Herschel-Bulkley model (for the range of shear rates tested). The evolution of the rheological characteristics (yield stress, viscosity) as a function of the total solid volume fraction have been placed on a graph in order to compare the behaviour of the natural materials with that of the artificial mixtures (Fig. 7).

It should be recalled that two types of mixture were tested, the first being a group of mixtures (marl and moraine) associated with localised movements on the north-facing slope (EA-POC, EA-

IND, EA-C1a, DA-COU99a, b) and the second (marl, moraine and sandstone) associated with movements on the south-facing slope (EA-VAL, DF-RBX, DF-FAU).

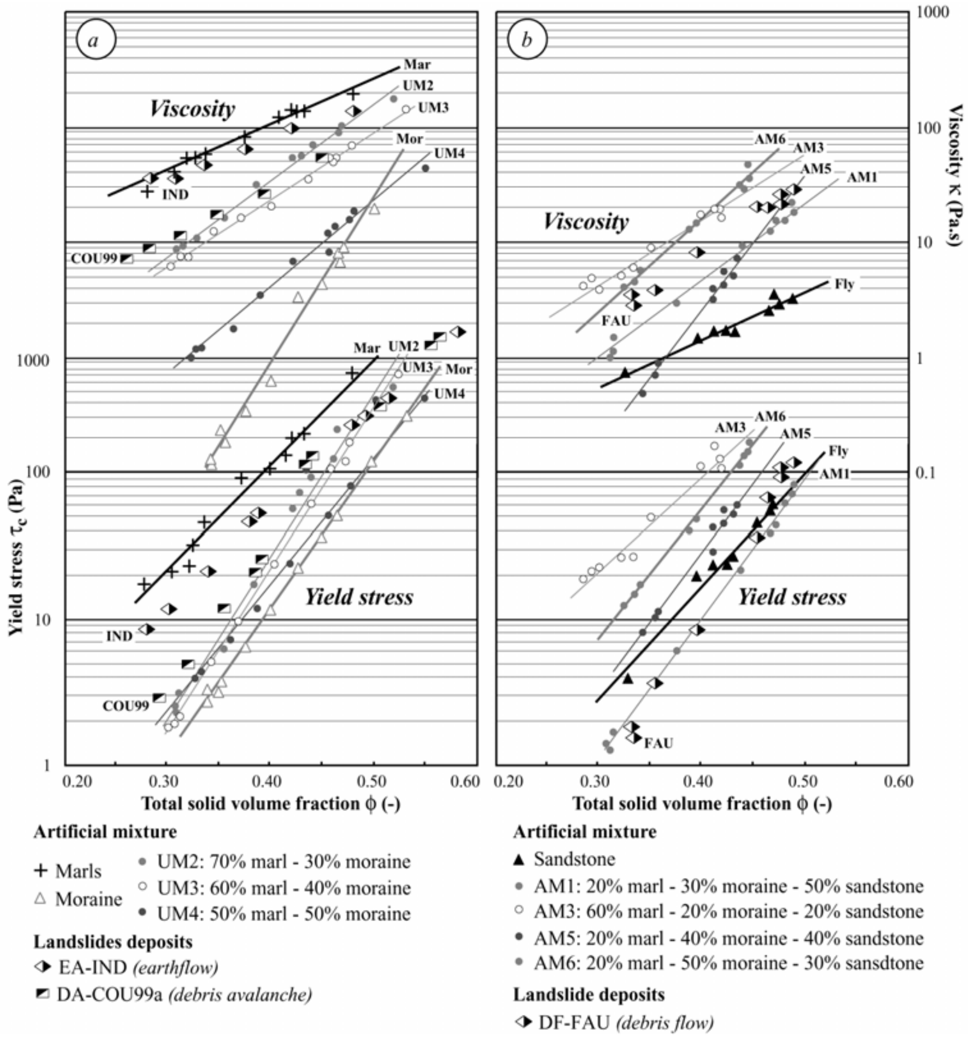

Figure 7. Variation of the rheological properties (yield stress and viscosity) as a function of the total solid volume, using the rheometrical tests, the slump tests and the inclined plane tests. Figure 7a represents the landslide material and artificial mixtures involving marl and moraine, Figure 7b represents the landslide material and artificial mixtures composed of marl, moraine and sandstone.

The natural and artificial mixtures both present the same type of relationship. For total solid volume fractions between 0.30 and 0.60 the yield stress may vary by as much as three times, while the viscosity varies only by twice as much. For both groups the yield stress and the viscosity increase with the percentage of black marl in the mixture and a flow threshold can be observed as soon as the proportion of black marls in the mixture is equal to at least 50%. There are no significant differences, however, in the behavior of artificial mixtures comprising moraine or sandstone. Moraine and sandstone present similar yield stresses for the same total solid fraction, while viscosity increases more rapidly with the solid fraction for moraine.

In the marl-moraine-sandstone mixtures the hypothetical mixtures with the greatest susceptibility to flow are all characterised by a moderate proportion of black marl in the mixtures (<50%). For the marl-moraine mixtures the UM4 mixture (40% moraine, 60% marl) presents the greatest susceptibility to flow. The behaviour of this mixture is very close to the behaviour of the EA-IND material (material from the DA-COU99a debris avalanche (Malet et al. in press).

The change in behaviour of the mixtures, depending on the constituents of the materials, relates particularly to the viscosity. A distinction in the mixtures can be observed, depending on the volume concentration. This is the case, for example, in the AM5 mixture which present a very low viscosity for $\phi = 0.35$, but it is much greater (higher than for the other mixtures) for total solid volume fractions over 0.45.

5 CONCLUSION

This study has demonstrated that materials from flow-like landslides which develop into earthflows, debris avalanches and debris flows triggered in black marl present a rheological behaviour in simple shear which can be described by a Herschel-Bulkley model where the geomechanical parameters increase with the solid volume concentration. The results obtained by various methods (rheometrical tests, slump tests, inclined plane tests) are satisfactory, because the differences noted for the yield stress and the viscosity were small (< 20 %). The similarities in the behaviour of materials enabled us to propose normalized master curves. The differences in the plasticity index for each material appear less obvious than the rheological parameters which distinguish two groups of materials according to the percentage of marl and moraine and/or sandstone. Nevertheless a classification of materials according to the flow mode using viscosity as parameter may be observed. The material which flowed fastest presented the lowest viscosity, regardless of the volume concentration; the materials *in situ* are the most viscous (Mar). A mixture of 40 % of moraine (or sandstone) and 60 % of marls presented the weakest yield stress and viscosity for field-measured solid concentrations. The presence of sandstone or moraine associated with marl did not change the behaviour of the mixture as a whole.

Moreover the key difference between muddy earthflows, muddy debris avalanches and muddy debris flows appears to be controlled by the fluid phase of the flow. The fluid phase consists of air, water, clay, silt and sand. The fluid phase in the debris avalanche and debris flow apparently has lower strength and viscosity in comparison to that of the earthflow. Nevertheless all flows may be described as macro-viscous flows.

These relations between yield-stress, viscosity and the textural properties of the material may be useful for identifying potential source zones in flow-like landslides areas. It may be useful in torrent hazard control by mapping flow susceptibility in terms of the grain-size distribution of the surficial formations.

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