Chapter 4

The Effects of Sediment Size and Concentration on the Rheological Behavior of Debris Flows

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Additional information is available at the end of the chapter

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Abstract

Sediment concentration, size, and distribution of grains play a relevant role defining the rheology of many geophysical flows. Experiments on slurries consisting of fine-grained and coarse-grained reconstituted debris flow mixtures having bulk volume concentration ranging from 0.32 to 0.42 are examined. The mixtures exhibit a typical yielding non-Newtonian flow behavior. Sediment concentration influences the rheological behavior of the mixtures, leading to dilatant or pseudoplastic flow. A generalized Herschel-Bulkley rheological model well represents the experimental data, whereas power index and consistent coefficient are expressed as a function of sediment concentration (i.e., void ratio). The presence of coarse grain fraction mainly influences yield stress. Increasing the relative content of coarser fraction, with respect to the finer fraction, leads to a diminishing of yield stress. Keeping constant the finer sediment content, the more relevant coarse fraction is the higher yield stress results.

Keywords: debris flows, fine-grained mixtures, coarse-grained mixtures, Herschel-Bulkley model, yield stress

1. Introduction

Granular-fluid mixtures are commonly present in natural flows, such as debris flows or mud flows, whose difference mainly lies in the sediment fine fraction content, which is determinant for the fluid rheological behavior.

Over the last decades, the risk of such geophysical phenomena has increased enormously because of the effects of climate change, and the effort to describe the flow properties has increased too, motivating experimental, numerical, and theoretical studies. Nevertheless, it is still an open question to define the universal features for different flow configuration. Even when using state-of-the-art technologies, it is still difficult to extract common features or a general trend for different flow configurations [1]. The difficulty mainly refers to the uncertainty in defining the most appropriate constitutive equations for the flowing materials, and the knowledge of the rheological behavior of these mixtures is crucial in any run out modeling, to assess the travel distance and the depositional area.

Indeed, debris flows behave as a concentrated grain-fluid mixture of variously assorted particles during the flow [2], and its bulk flow properties can be assessed from the study of the involved soil-liquid mixture accounting for the effects due to particle size distribution and solid volumetric concentration above all [3–8].

In literature, many different models for both dry granular flows and fluid-granular mixtures may be found but they do not provide a unique rheological formula for the mixture [1, 2, 9–13]. One of the most popular approaches considers the debris flow as a non-Newtonian fluid with an empirical Bingham rheology. This methodology shows good results in case of viscous flow (e.g., pure mudflows) [14–16]; conversely, it is not suitable for the case of noncolloidal particles involved in the flowing mixture (i.e., granular flow) [17], in which not only the fluid viscosity but also the grain-fluid interactions have to be taken into account.

Solid volumetric concentration and particle size distribution greatly influence the behavior of granular suspensions: usually, the finest particles are very sensitive to Brownian motion effects or colloidal forces, whereas, coarse particles experience frictional or collisional contacts and hydrodynamic forces. Therefore, the bulk behavior of particle suspensions is very complex and depends on many parameters: solid volumetric concentration, size and shape of the particles, size distribution, the nature of the interstitial fluid, etc.

Accounting for the presence of a large range in sediment size in natural debris flow, the first step may be to understand how the finer (i.e., colloidal fraction) and the coarser (i.e., silty and sandy) fractions contribute to the rheology of the mixture.

Sengun and Probstein [18] carried out experimental investigations and theoretical analysis on coal slurries. They observed that on one hand, the fine (colloidal) fraction seems to perform independently of the coarse fraction and that the fluid matrix, composed by the interstitial liquid and the finest fraction, confers most of its rheological characteristics to the bulk mixture. On the other hand, the coarser particles significantly contribute to the viscosity variation via processes of hydrodynamic dissipation. The experimental work performed by Coussot and Piau [19] on natural debris flows mixtures confirmed that the amount of finest fraction influences the main rheological parameters of the entire suspensions, and that the yield stress strongly varies with the amount of coarse particles. It is in agreement with the observations of Ancey and Jorrot [20] derived from their laboratory experience on coarse particles dispersed in a clay suspension. In fact, they put in evidence that the fine-grained fraction is responsible of the rheological behavior of the bulk mixture, if large particle fraction is smaller than fine particle fraction. Ancey and Jorrot [20] also illustrated that the grain size distribution has relevant effects on the yield stress value: it increases proportionally to the solid concentration of coarse fraction if it is dominant in bulk volume of the mixture.

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The works carried out in the last decades on a large amount of collected data indicate the Hershel-Bulkley model as the most appropriate to describe the rheological behavior of simple yield stress fluid in a large range of shear rate (i.e., 10^{-1}–10^{2} s^{-1}) [21]. Referring to the steady state flow-like regime of debris flows, rheological parameters may be expressed as a function of the bulk volume sediment concentration, whereas the yield stress greatly depends not only on the sediment concentration but also on the relative content of finer and coarser grain [22].

This chapter presents recent experiments [22] on reconstituted debris flows mixture, stressing the effects on the rheological behavior due to the sediment concentration and the presence of coarse-grained fraction.

Experimental activities carried out with rotational rheometer and inclined plane are presented separately. The former was mainly oriented to study the effects associated with sediment bulk volume concentration on the flow-like regime (i.e., steady state shear condition), whereas the latter was focused on the effects on the yield stress [23] due to the presence of coarse grains.

According to the experiments, the rheological behavior of the mixture are very much influenced by sediment concentration, and in the flow-like regime, it may change from shear thinning to shear thickening, depending on the sediment concentration. It is demonstrated that a generalized Herschel-Bulkley rheological model well represents the flow-like regime of the slurries, being consistent coefficient and power index function of the void ratio of the mixture. Both of them present a limiting value in case of vanishing sediment content and approaching the maximum theoretical sediment concentration, despite the soil characteristics, which affects the fitting parameters. The inclined board experiments put in evidence the role of the sediment concentration and of the coarser grain fraction content on the yield stress.

2. Tested materials and experiments

Materials investigated and experimental methods are widely described in [22]. The investigated materials come from the source area of two real debris flows event occurred in May 1998 (soil B-Montefiorino Irpino) and in March 2005 (soil A-Nocera) in Campania region (southern Italy), which involved the pyroclastic terrains, originated by the volcanic activity of Somma-Vesuvio mount, covering the mountains of that region. Picarelli et al. [24] report an extensive description of their geotechnical characteristics, and several preliminary works have been performed on these materials [25–27].

Figure 1 shows grain size distribution of the collected samples; the soils are sandy silt with a very limited clay fraction. The clay part is slightly plastic though only in the Vesuvian deposits. The gravel part mainly consists of pumices, and secondarily of scoriae and lapilli. The particles are mainly siliceous, and their structure is amorphous and porous (i.e., double porosity system inter- and intra-particle) [24].

The mean physical properties of the sampled soils A and B are specific gravity of soil particles G_S = 2.57, 2.62; dry weight of soil per unit volume γ_d = 7.11, 9.08 kN/m^3; total weight of soil per

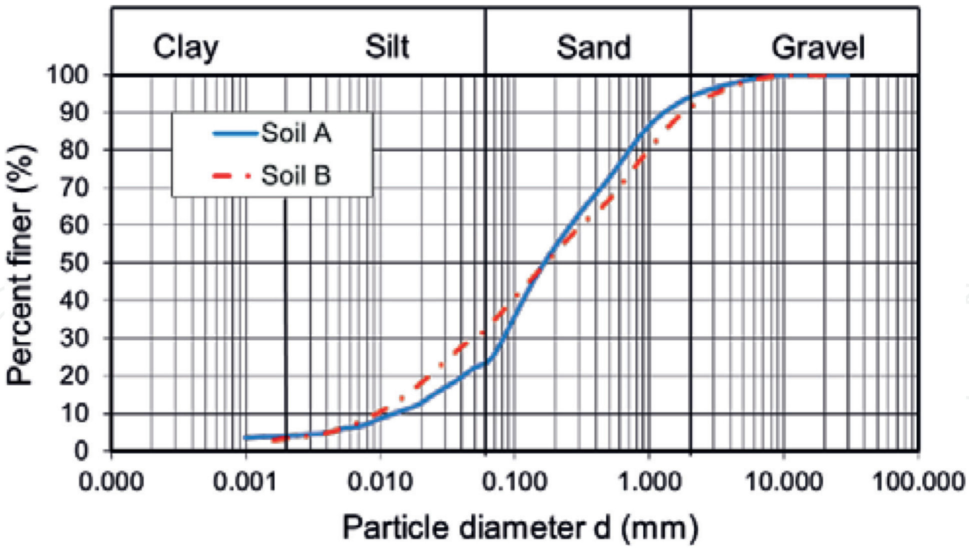

Figure 1. Grain size distribution of the natural soil.

unit volume γ = 12.11, 11.35 kN/m^3; porosity p = 0.71, 0.66; degree of saturation Sr = 0.71, 0.35. Scotto di Santolo et al. [26] reports the extensive description of the geological and geotechnical soils characteristics.

The reconstituted debris flow samples (see **Table 1**) were prepared removing the organic elements and drying out in an oven at 104°C for a day. Then, an appropriate amount of distilled water was used to obtain a soil-water mixture of desired total volumetric concentration Φ_T (ranging from 30 to 42%):

$$\Phi_T = \frac{V_s}{V_s + V_w} \tag{1}$$

where V_S is the volume of solids and V_w the volume of water.

Laboratory activity consists of 22 tests herein reported in **Table 1** as a sack of comprehension. Experiments of Group I refer to fine-grained mixture (having maximum size of grain diameter d = 0.5 mm), whereas Group II and III refer to coarser fraction (i.e., having sediment diameter d > 0.5 mm). The latter are subdivided into four classes: the first two correspond to coarse sand (0.5 mm < d < 1.0 mm) and very coarse sand (1.0 mm < d < 2.0 mm). The latter two (2.0 mm < d < 5.0 mm and 5.0 mm < d < 10.0 mm), are set accounting for the maximum grain size diameter of the collected samples.

The total solid volumetric concentration Φ_T, refers to the bulk volume:

$$\Phi_T = \Phi_f + \Phi_c \tag{2}$$

where Φ_f and Φ_c are the solid volumetric concentration referring to the fine-grained and coarse-grained mixtures, respectively:

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$$\Phi_f = \frac{V_{sf}}{V_{sf} + V_{sc} + V_w} \tag{3}$$

$$\Phi_c = \frac{V_{sc}}{V_{sf} + V_{sc} + V_w} \tag{4}$$

In Eqs. (3) and (4), the subscript f, c, w and s refer to fine-grained, coarse-grained materials, water and soil, respectively.

Test	**Group**	**Φ_T(%)**	**Φ_f°(%)**	**Φ_c(%)**				**Φ_c(%)**	**Soil**
				d < 1 mm	**d < 2 mm**	**d < 5 mm**	**d < 10 mm**		
0*	I	32	32					—	A
1*	I	35	35					—	A
2*	I	38	38					—	A
3*	I	40	40					—	A
4*	I	42	42					—	A
5*	I	30	30					—	B
6*	I	32	32					—	B
7*	I	35	35					—	B
8*	I	38	38					—	B
9**	IIa	30	22	8	—	—	—	8	B
10**	IIa	30	17	8	5	—	—	13	B
11**	IIa	30	15	8	5	2	—	15	B
12**	IIa	30	14	8	5	2	1	16	B
13**	IIb	32	24	8	—	—	—	8	B
14**	IIb	32	19	8	5	—	—	13	B
15**	IIb	32	16	8	5	3	—	16	B
16**	IIb	32	15	8	5	3	1	17	B
17**	III	25	25	—	—	—	—	—	B
18**	III	33	25	8	—	—	—	8	B
19**	III	38	25	8	5	—	—	13	B
20**	III	40	25	8	5	2	—	15	B
21**	III	41	25	8	5	2	1	16	B

*Rotational rheometer test.
**Inclined plane test.

Table 1. Experimental program.

2.1. Fine-grained mixture: experimental device and procedure

Fine-grained mixtures tests were performed using a rotational rheometer equipped with vane rotor system. Assuming inertia effects and normal stress differences being negligible, it was possible to derive the shear stress (τ) and the shear rate ($\dot{\gamma}$) from the torque applied to the vane and the angular velocity of the vane rotor, accounting for geometrical device's characteristics [28].

After the complete homogenization of the mixture was ensured, the run-up shear stress ramp started, increasing the applied stress from 0.1 Pa to the maximum stress value (by step of 0.001 Pa). Then, the decreasing shear stress ramp was imposed following the same stress-step, until the initial stress value was applied.

2.2. Coarse-grained mixture: experimental device and procedure

Experiments on coarse-grained were carried out by inclined plane test. It consists of splitting the suspension on the horizontal rough plane in order to obtain a wide layer of material. The tray is progressively inclined until a threshold inclination corresponding to a blatant motion of the mass front, and the experiments were carried on until the full stoppage of the flowing mixture. Accounting for the still, threshold and stoppage condition, and according to the lubrication assumption (i.e., still material thickness much smaller than its longitudinal extent; [29]), it may be assumed a uniform flow condition for the slurry, and momentum balance gives the shear stress distribution within the mixture [22, 29].

2.3. Comparability between sweep test and inclined plane test

The first question is how much the different equipment may give comparable results, and hence if they may be used as alternative method in analyzing rheological behavior. To aim this, inclined plane test on fine-grained mixtures obtained with materials A and B were carried out at the same sediment concentration considered in runs 1–8 (see **Table 1**), and results were compared to those obtained via sweep test. Both in case of rotational rheometer and inclined plane test, the dynamic and static yield stress increase with the solid volumetric concentration and the static yield stress is higher than the dynamic one. Yield stress values obtained from inclined plane are consistent with those resulting from sweep tests, even though the inclined plane test leads to a slight overestimation of the yield stress values according to previous observations [27]. Therefore, inclined plane test may represent a suitable alternative to investigate yielding behavior of dense granular flow mixtures, and it overcomes the shortcoming arising from geometrical limitation of standard rheometer, which confines its operability just to fine-grained slurry (i.e., maximum sediment size smaller than few hundred microns).

3. Flow curves

All the suspensions exhibit a non-Newtonian behavior and the shear stress level increases with the sediment concentration for both soil A and soil B. The experiments show a marked sensitivity of the rheological behavior to granular concentration. **Figures 2** and **3** report stress-strain curve obtained in case of soil A and soil B, whereas **Figures 4** and **5** depict the apparent viscosity $(\eta = \tau/\dot{\gamma})$.

Both yield stress and ultimate apparent viscosity (i.e., viscosity corresponding to the higher stress-strain values) vary over the order of magnitude among the tested solid concentration (ranging from 32 to 42%). The apparent viscosity trend is monotonically decreasing with the shear stress and it tends to a constant value for higher shear stress value. Its values increase, increasing the sediment concentration in both cases of soil A and soil B.

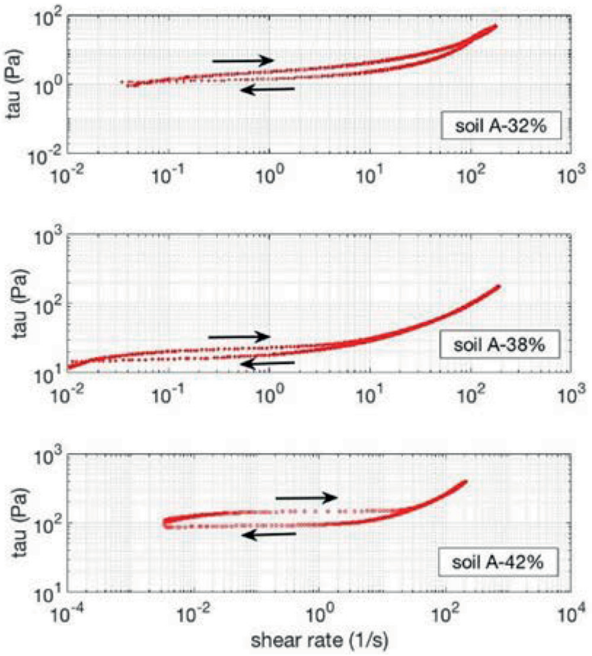

Figure 2. The shear rate $\dot{\gamma}$ versus the shear stress τ for soil A samples. The arrows indicate the increasing-decreasing applied shear stress ramp.

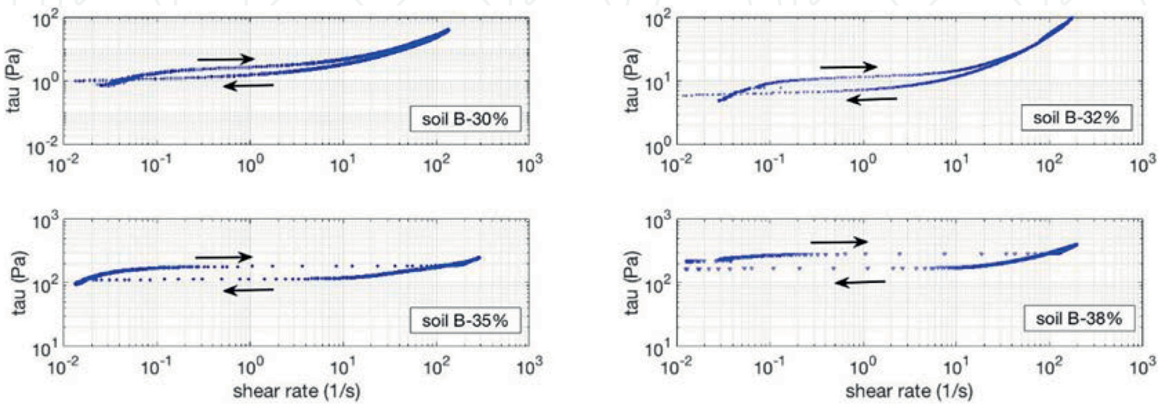

Figure 3. The shear rate $\dot{\gamma}$ versus the shear stress τ for soil B samples. The arrows indicate the increasing-decreasing applied shear stress ramp.

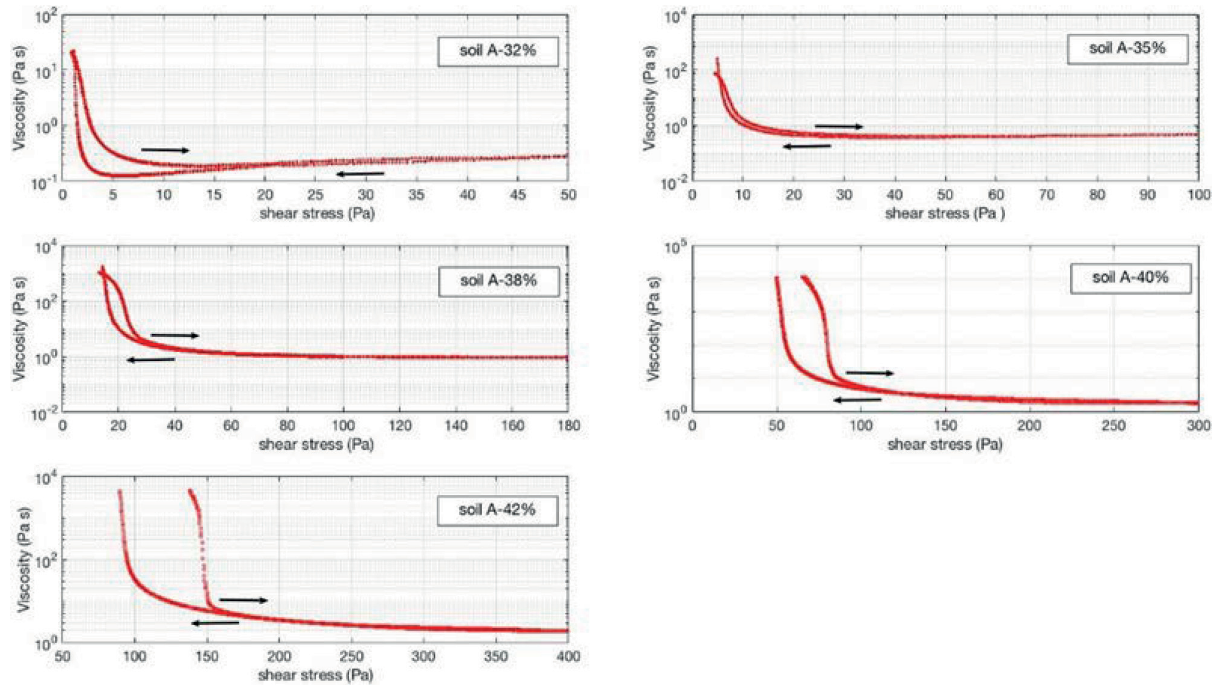

Figure 4. The viscosity η versus τ for soil A samples. The arrows indicate the increasing-decreasing applied shear stress ramp.

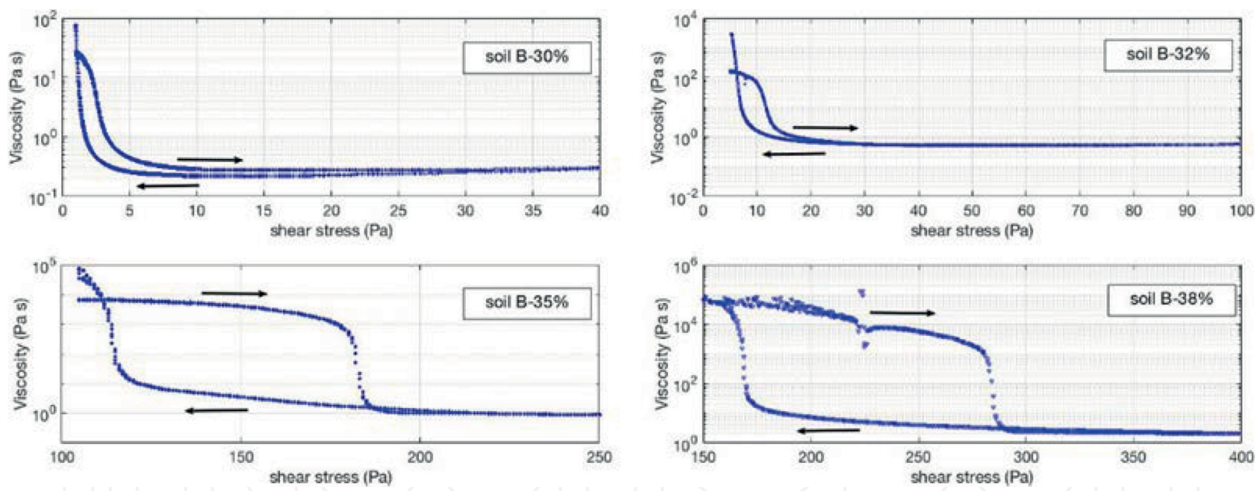

Figure 5. The viscosity η versus τ for soil B samples. The arrows indicate the increasing-decreasing applied shear stress ramp.

It is worth noting thixotropic behavior, as it is evident from the flow curves (**Figures 2**, **3**), which exhibit a stress level independent on the shear rate (for shear rate less than 10^0–10^1 s^{-1} depending on sediment concentration) having different values between increasing and decreasing shear stress ramp. The behavior of these granular-fluid mixtures at flow initiation and flow stalling put in evidence that the timescale of microstructure destruction is not the same as that of restructuralization, and it reflects on the yield stress [30]. Notwithstanding the existence of a yield stress, which marks the transition between solid and fluid state, it is still a

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controversial issue [31], it may be defined a static yield stress τ_{c1}, that is, the critical stress allowing steady state flow (run-up test), and the dynamic yield stress τ_{c2} corresponding to the complete stoppage of the flowing material.

Hysteresis may be better appreciated in **Figure 6** showing a representative sweep test. Increasing the stress level around a critical value (i.e., the static yield stress τ_{c1}), leads to a large increasing of the resulting shear rate, until it reaches the value associated with the end of the stress plateau. It may be considered as a critical value $\left(\dot{\gamma}_{c1}\right)$, which represents the transition of the material mixture from a yielding to a steady state flow behavior; in fact, no steady flows can be obtained below the critical shear rate [32]. According to the run-down curve, the viscosity remains almost constant over a large range of applied shear stress (**Figures 4** and **5**), since its rate dramatically change in correspondence of the beginning of the stress plateau: it corresponds to the dynamic threshold condition ($\dot{\gamma}_{c2}$, τ_{c2}).

Referring to dynamic threshold condition, and assuming a representative value for critical shear rate ($\dot{\gamma}_c = 0.1\ \mathrm{s}^{-1}$), the critical shear stress (τ_c) was then estimated from the plateau region in the stress-strain curve by averaging shear stress values, and eventually the dimensionless shear rate and shear stress can be introduced:

$$T = \frac{\tau}{\tau_c} \tag{5}$$

$$G = \frac{\dot{\gamma}}{\dot{\gamma}_c} \tag{6}$$

Dimensionless values are useful to compare different material, despite of total solid concentration. In fact, all the curves collapse to a single one in the range of plateau occurrence

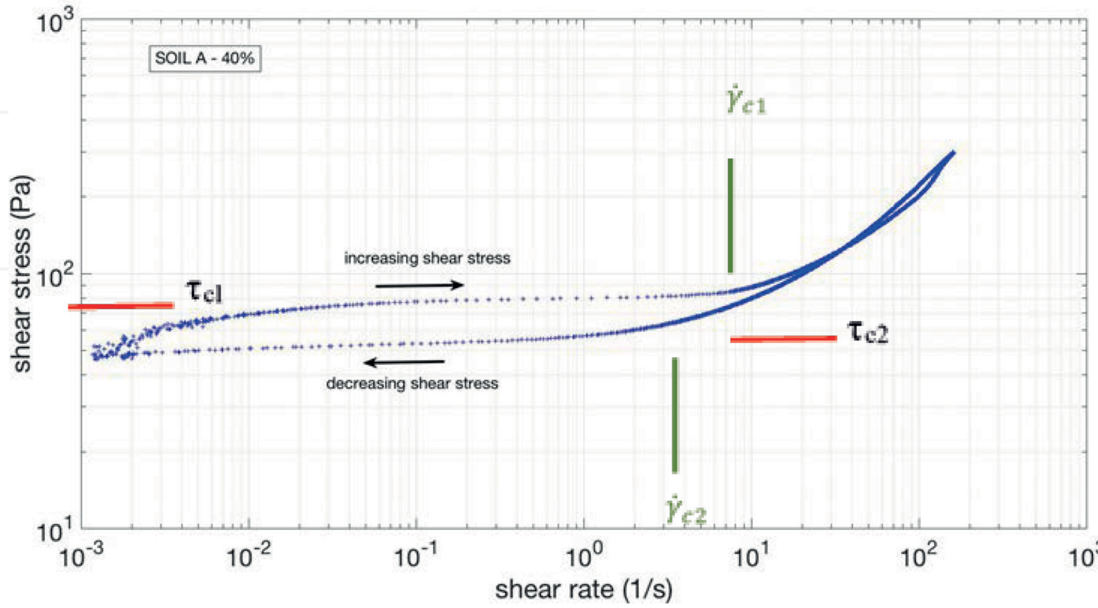

Figure 6. Representative flow curve.

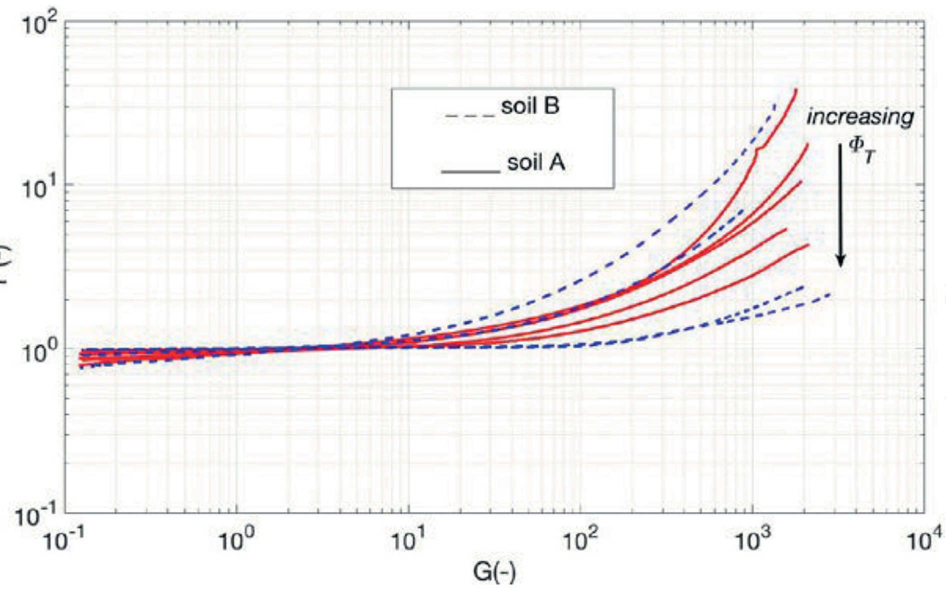

Figure 7. Soil A and soil B. Dimensionless flow curves.

(i.e., around $G = 1$). On the opposite, grain content significantly affects the flow-like regime, and the lower the solid concentration is the higher the stress rate results, independently on the considered soil (**Figure 7**). It is also evident the scatter from the Bingham fluid idealization.

4. Inclined plane results and the effects of grain size distribution on the yield stress

Ancey and Jorrot [20] studied the effect of clay content and concentration of noncolloidal grains on the yield stress, without describing in detail the effects due to granular size distribution, resulting a yield stress model depending on fitting parameters to be extrapolated from experimental results. More recently, Yu et al. [33] performed experimental study on the role of coarse grain in yield stress, and they suggested a yield stress model accounting for an equivalent volumetric solid concentration depending on material characteristics, sediment size, and sediment shape. The model needs some strong approximation, thus it does not present yield stress as a continuous function of sediment concentration. Another aspect related to different grain size refers to particle segregation during flow, which affects the behavior of dense-shared granular flows that are free to dilate [34].

It is generally believed that sediment concentration affects yield stress condition, and shear stress can be expressed as an exponential function of sediment concentration [35–37]. In recent laboratory experiments, Jeong [38] found that little change of silt and sand particles strongly modified the flow behavior, so that increasing sand content, debris flow rheology tends to be more Bingham-like behavior.

It remains still an open question as which are the effects due to grain size distribution on the rheology of debris flows. To this aim, it may be considered the inclined plane test of Group II and III in **Table 1**. Group II tests are mainly oriented to study the effects of increasing the presence of coarse fraction with respect to the total solid volumetric concentration, whereas Group III tests are devoted to stress the effects due to the increasing content of coarse particles, keeping constant the volume of finer grain.

Group II refers to mixtures having constant grain volume concentration ($\Phi_T = 30\%$, Group IIa and $\Phi_T = 32\%$, Group IIb), varying the relative content of fine and coarse grains. **Figure 8** reports the static and the dynamic yield stress, as a function of total solid volumetric concentration Φ_T and solid volumetric concentration of fine particles Φ_f:

$$\Phi_T/\Phi_f = 1 + \Phi_c/\Phi_f = 1 + V_{sc}/V_{sf} \tag{7}$$

Run 5 and run 6 related to fine-grained mixtures, are also accounted for, as a reference tests.

Group III consists of mixtures having a constant content of fine particle $\Phi_f = 25\%$, and a different concentration of coarse particle Φ_c. **Figure 9** depicts the yield stress value as a function of relative concentration Φ_T/Φ_f.

At constant total solid volumetric concentration Φ_T, the presence of a limited amount of coarse grain leads to a significant reduction on the static and dynamic yield stress, regardless the total solid concentration (see **Figure 8**). Moreover, the less fine grains content is the less yield stress values (both static and dynamic) are, regardless of the coarse particles fraction in the mixtures. The static and the dynamic yield stresses decrease over one order of magnitude if the finer particle content is larger than the coarser grain one. On the opposite, in presence of a comparable content of coarse and fine particle, yield stress slightly varies.

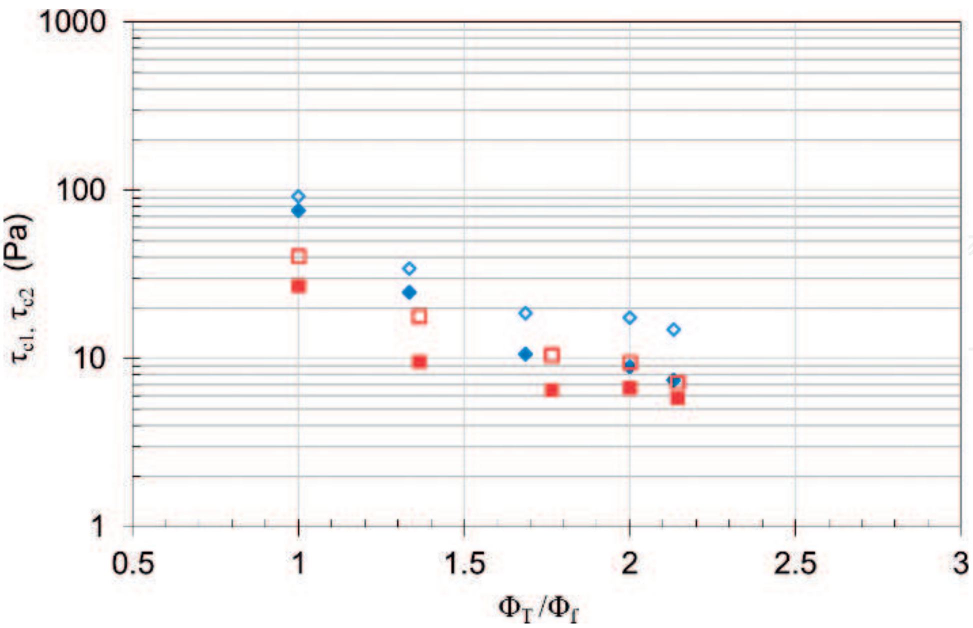

Figure 8. Material B ($\Phi_T = 30\%$–red squares, and $\Phi_T = 32\%$–blue diamond). Static (empty symbols) and dynamic (filled symbols) yield stress as a function of the ratio between total solid volumetric concentration Φ_T and solid volumetric concentration of fine particles Φ_f (tests #5, #6, and #9–16, see **Table 1**).

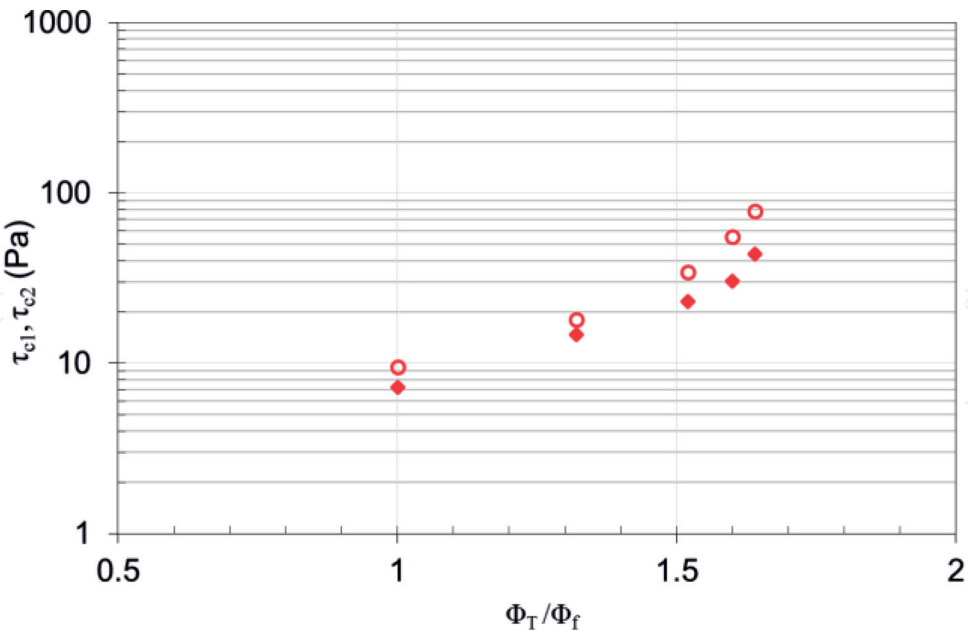

Figure 9. Material B (Φ_f = constant = 25%). Static (empty symbols) and dynamic (filled symbols) yield stress as a function of the ratio between total solid volumetric concentration Φ_T and solid volumetric concentration of fine particles Φ_f (test #5 and tests #17–21, see **Table 1**).

At constant fine particles fraction (**Figure 9**), the increment of coarse grains concentration leads to a significant increase of the yield stress (over one order of magnitude). On the opposite, increasing the volumetric fraction of coarse grains leads to a consistent increasing of the yield stress values.

5. Rheological model

The choice of the most appropriate rheological model is of paramount importance analyzing debris flows, and modeling the runout and deposition fan of slurry flows, which in turn represent the most important aspects in assessing risk associated with geophysical phenomena. A thixotropic flow model may represent both initial structure jamming and aging effects, whereas the non-Newtonian time-independent yield stress model implies the complete reversibility of stress–strain relationship. In many cases, the Herschel-Bulkley model results very similar to the time-dependent thixotropic model [30], and it has widely implemented in viscous-flow simulations [39, 40], even though it still remains challenging the treatment of the non-smoothness constitutive equation [41].

In effect, this chapter focuses on the constitutive equation assuming a simple shearing non-Newtonian flow. Among the varieties of models proposed in literature, the Herschel-Bulkley model seems more appropriate to describe the rheological behavior over the entire range of dynamic condition herein explored, in fact stress–strain rate does not seem linearly proportional in the flow-like regime (see **Figure 7**):

$$\tau = \tau_c + k \cdot \dot{\gamma}^n \tag{8}$$

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where k indicates the consistent coefficient, n the power index ($n > 0$ pseudoplastic fluid; $n < 1$; dilatant fluid; $n = 1$ results the Bingham law).

Several other works (e.g., [35, 42]) have already put in evidence that the total solid concentration strongly influences the rheological behavior of granular-fluid mixtures, and it reflects on Herschel-Bulkley generalized model parameters. In the following, the flow-like regime and the yielding condition will be examined separately.

In the range of the stress–strain curve typical of flow-like behavior (i.e., at shear rate greater than 10^0–10^1 s^{-1}), the excess of stress with reference to the yield stress increases with the shear rate, and both parameters k and n result as a function of total sediment concentration (**Figure 10**). Fitting rheological parameters of Herschel-Bulkley model is not trivial. Usually the yield stress τ_c is defined extrapolating the experimental flow curve for vanishing shear rate. In fact, both consistent coefficient k and power index n are very sensitive to the yield stress value [43].

Therefore, it is preferable to split the fitting procedure: first power index n was estimated applying a method proposed by Mullinex [43] no matter of consistent coefficient k or yield stress τ_c. Then, yield stress τ_c was calculated averaging stress value over the plateau region of the flow curve; eventually assuming the already estimated τ_c and n values, parameter k was fitted to the experimental curve (see **Table 2**).

In order to show the influence of grain content on the model's parameter, it is convenient referring to the void ratio (e_0) instead referring to the bulk volume concentration Φ_T:

$$e_0 = \frac{1 - \Phi_T}{\Phi_T} \tag{9}$$

Corresponding to the higher and lower values of void index e_0, the rheological parameters tends to a limiting values (both in case of soil A and B), as it is shown in **Figures 11** and **12**.

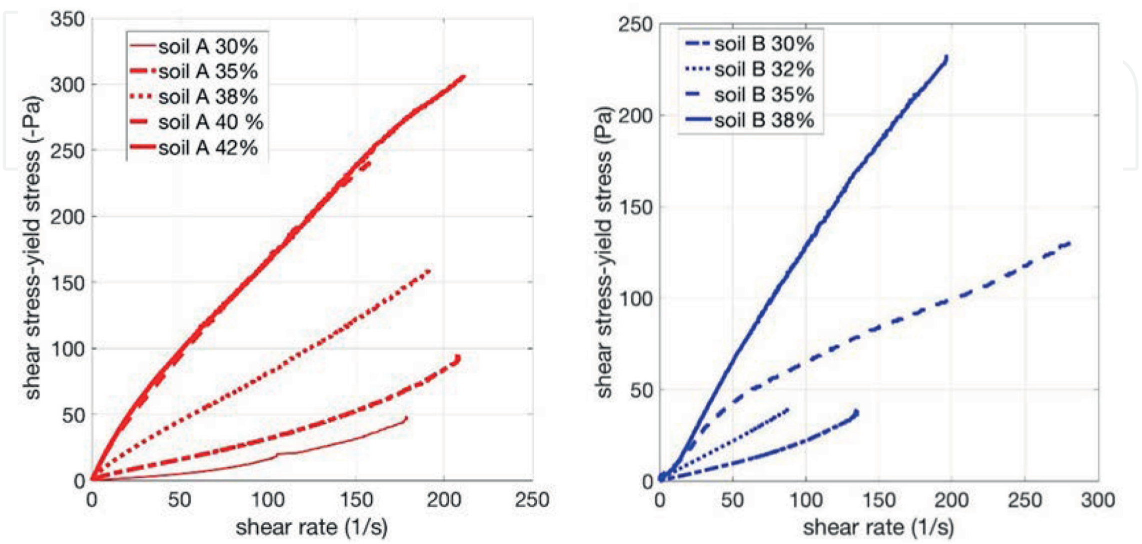

Figure 10. The excess of shear stress with reference to the yield stress versus the shear rate for soil A and soil B tests.

Test	Soil	Φ_T(%)	τ_c(Pa)	n	k(Pa s^n)
0	A	32	1.4	1.863	0.003
1	A	35	5.0	1.382	0.055
2	A	38	15.0	0.921	1.236
3	A	40	53.5	0.796	4.236
4	A	42	90.0	0.795	4.526
5	B	30	1.2	1.402	0.036
6	B	32	6.5	1.167	0.212
7	B	35	113.5	0.770	1.700
8	B	38	169.0	0.874	2.294

Herschel-Bulkley rheological parameters.

Table 2. Sweep test on soil A and soil B.

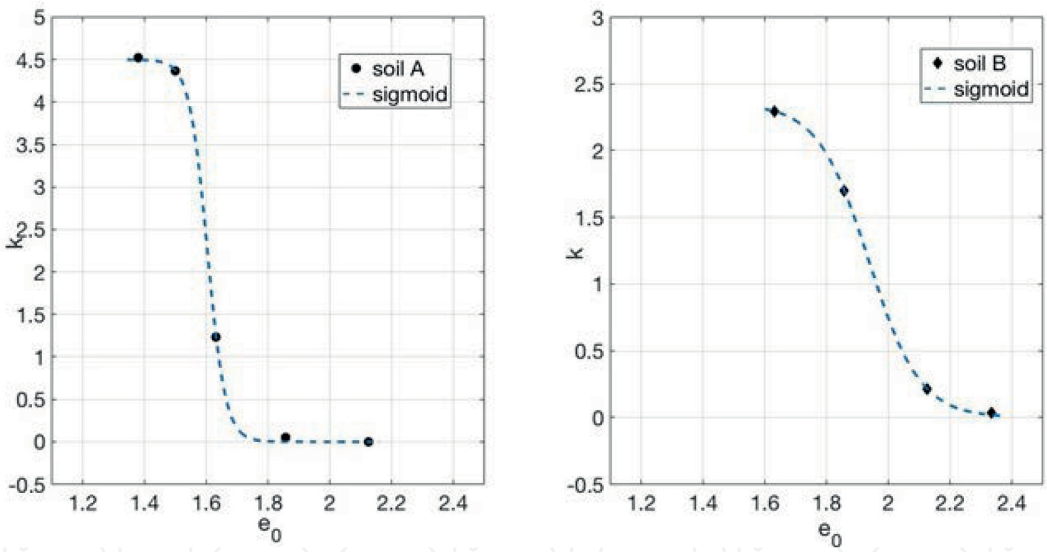

Figure 11. Soil A and B. Consistent coefficient k as a function of void ratio e_0. Sigmoid functions Eq. (10) are plotted according to fitting parameters (see **Table 3**).

These trends suggest considering a sigmoid functions:

$$k(e_0) = \frac{\alpha}{1 + e^{-\lambda(e_0 - \beta)}} + \zeta \tag{10}$$

$$n(e_0) = \frac{a}{1 + e^{-l(e_0 - b)}} + z \tag{11}$$

where a, b, l, z, α, β, λ, and ζ are fitting parameters depending of mixture characteristics, and their values are shown in **Table 3**.

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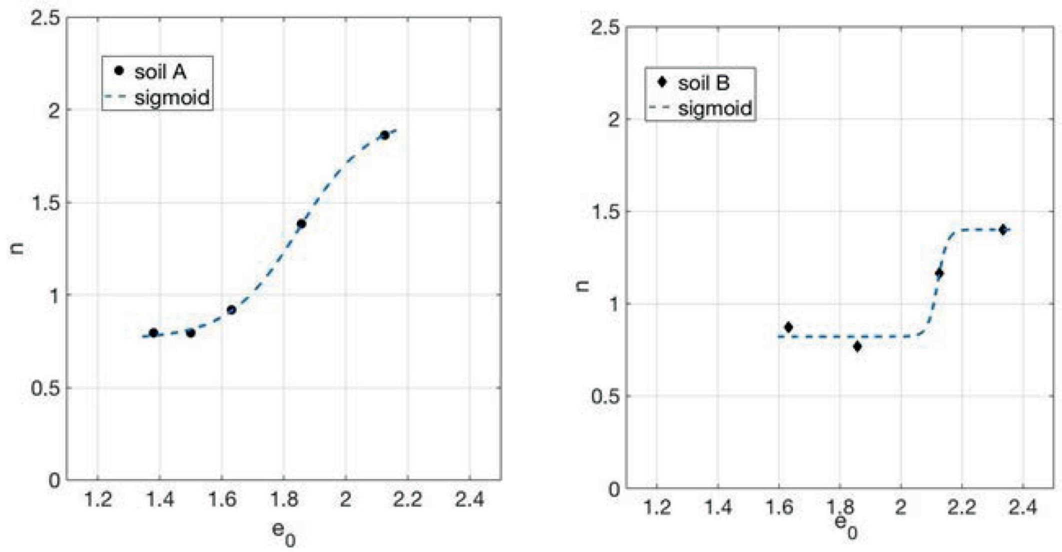

Figure 12. Soil A and B. Power index n as a function of void ratio e_0. Sigmoid functions Eq. (11) are plotted according to fitting parameters (see **Table 3**).

Soil	*a*	*b*	*l*	*z*	α	β	λ	ζ
A	1.200	1.85	8.808	0.762	4.5	1.603	−34.18	0
B	0.580	2.12	62.79	0.822	2.35	1.936	−12.16	0

Sigmoid functions' parameters Eqs. (10) and (11).

Table 3. Soil A and soil B.

6. Conclusion

Experiments on debris flows reconstituted mixtures analyzed in the present study involves pyroclastic soils presenting a very small clay fraction. They show a behavior of non-Newtonian fluids with yield stress according to several other previous works [15, 22, 44]. Stress–strain curve significantly depart from Bingham idealization, and varying the solid volume concentration, the mixtures show dilatant or pseudoplastic flow behavior, depending on the granular concentration, no matter of the considered soil characteristics. According to other studies [35], the solid content greatly affects the behavior of these mixtures during the flow, as it is evident studying the influence of the solid volumetric concentration on the rheological parameters of the mixtures.

Accounting for the run out and stoppage phase of debris flow, we may refer to the dynamic yield stress and to a simple shearing regime (i.e., simple yield stress fluid) [45]. Under this assumption, Herchel-Bulkley model reasonably applies to the experimental flow curve. The power index varies in the range n = [0.87–1.86] over the whole set of experiments; it shows a dilatant fluid behavior for the lower grain volume concentration, and progressively tends to a shear thinning fluid increasing the sediment content. Analogously consistent coefficient k [0.003–4.526] varies with sediment concentration or sediment void ratio, which seems more appropriate in order to define functional relationships.

Both parameters show a limiting value corresponding to the higher and the lower grain content. Therefore, the proposed rheological model applies a sigmoid function for both consistent coefficient and power index, whose fitting coefficients depend on mixture characteristic.

The inclined plane experiments at constant sediment bulk volume, show that increasing the relative content of coarser fraction leads to a diminishing of yield stress. On the other hand, keeping constant the finer sediment content, the more relevant coarse fraction is the higher yield stress results.

The relative concentration of coarse and fine particle seems to discriminant the rheological behavior. In the presence of dominant fine grain fraction, slight increase of the coarse grain fraction leads to a dramatic decrease of both static and dynamic yield stress values. When the concentration of coarse particles in the mixture increases and become similar to that of fine particles, the values of the rheological parameters more slightly decrease.

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Conflict of interest

The authors declare no conflict of interest.

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