EXPERIMENTS ON THE EFFECTS OF FINE-COARSE GRAINS CONTENT ON THE YIELD STRESS OF NATURAL DEBRIS FLOWS

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KEY POINTS

- *Debris flow rheology.*
- *Inclined plane tests on fine-coarse grained mixtures.*
- *Effects of coarse sediment on the yield stress of natural debris-flows.*

1 INTRODUCTION

The yield stress is an important parameter to describe flow characteristics of natural flows, such as slurries, mud and debris flows, which causes fatalities, injuries and landscape changes worldwide. Many studies have been carried out devoted to the determination of yield stress of granular-fluid mixtures, and some progress has been made in recent years. It is not surprising that the interaction between solid and liquid phase could approach different behaviour. In fact the effects of Brownian motion and colloidal forces control the finest solid fraction, whereas, frictional and collisional contacts and hydrodynamic forces govern the coarser particles content. Therefore, the bulk behaviour of viscous suspensions is very complex and the effects of many parameters (e.g., solid volumetric concentration, size and shape of the particles, nature of the interstitial fluid, etc.) must take into consideration to analyse their hydrodynamic behaviour. *Yu et. al*. (2013), show that sediment volumetric concentration and coarse particle size distribution have much larger effects on the yield stress than the finer sediment (i.e., clay). Previous experimental works on coarse particles dispersed in a clay suspension (e.g. *Ancey & Jorrot*, 2001) and on natural debris flows mixtures (e.g. *Coussot & Piau*, 1995), confirm that the amount of finest fraction influences the main rheological parameters of the entire suspensions in terms of fluid-like flow behaviour of the slurries (*Pellegrino & Schippa*, 2018), whereas the yield stresses strongly vary with the amount of coarse particles (*Major & Pierson*, 1992). The present experimental work aims to enlarge the knowledge on the contribution of grain size distribution (referring to the coarser particle content) on the rheological behaviour of debris flow mixtures with particular attention to the transition process from a solid-like to fluid-like flow behaviour.

2 EXPERIMENTS.

Inclined plane tests have been carried out involving samples collected from the source area of two real debris flows event occurred in Campania region (southern Italy), which involved the pyroclastic terrains covering the mountains of that region. The collapsed soils (i.e. soil A and soil B) are both pyroclastic, and belong to the most recent deposits originated by the volcanic activity of Somma/Vesuvio mount. The soils are sandy silt with small clay fraction (see fig.1 (a)), having a specific gravity G_S=2.56-2.62, and are the dry weight of soil per unit volume γ_d=9.08-7.11 KNm^{-3}, the total weight of soil per unit volume γ=11.35-12.11 KNm^{-3}, porosity p=0.66-0.71 respectively. *Scotto di Santolo et al*. (2010) reports the extensive description of the geological and geotechnical soils characteristics. According to the grain size distribution, the finer fraction is limited by d=0.5 mm, which corresponds to the limiting value of medium sand (Wentworth scale). Coarser fraction was subdivided into 4 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), were set accounting for the maximum grain size diameter of the collected samples. The testing samples is prepared mixing the dry soils, with an appropriate amount of distilled water in order to have a desired bulk volume concentration Φ_T*:* Let Φ_f and Φ_g the solid volumetric concentration referring to the fine and coarse-grained mixtures respectively, V the volume (the subscript *sf, sg* and *w* refer to fine-grained, coarse-grained materials and water respectively):

$$\Phi_T = \Phi_f + \Phi_g \qquad \Phi_f = \frac{V_{sf}}{V_{sf} + V_{sg} + V_w} \qquad \Phi_g = \frac{V_{sg}}{V_{sf} + V_{sg} + V_w} \tag{1}$$

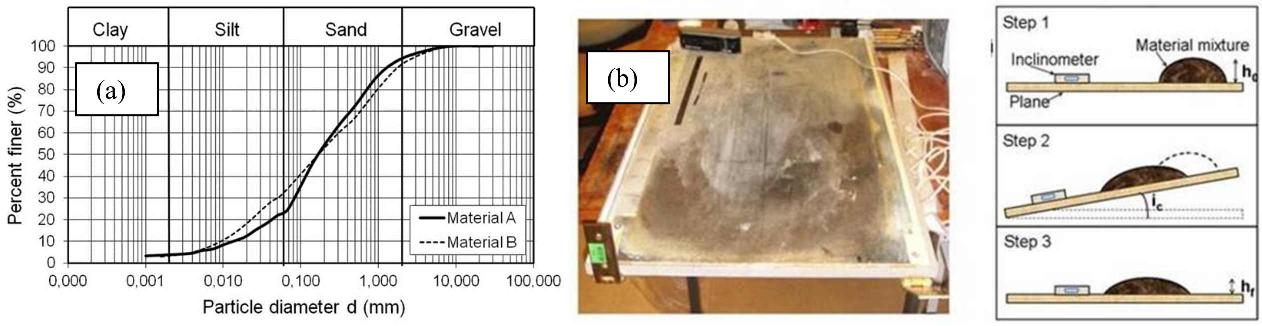

Figure 1. (a) Soil A and B: grain size distribution; (b) inclined plane and schematic of a run: step 1-initial volume of suspension at rest (horizontal); step 2-flowing and stopping suspension (inclined); step 3-measuring characteristic parameters

Inclined plane (fig. 1(b)) consists of a small plywood rectangular board (2 m long and 1 m wide) having a rough plane surface equipped with an inclinometer. A typical inclined plane test consists of splitting the suspension on the horizontal rough plane in order to obtain a wide layer of material. Initially, the sample thickness (h_0) is measured in different position in the central region of the mixture at a distance from the mixture edges larger than 3 times of the maximum mixture thickness. Subsequently, the board is progressively inclined in order to reach a critical angle value (i_c) corresponding to a notable motion of the mass front, and test continues until the full stoppage of the mass. Eventually, the final thickness (h_f) of the mixtures measured, according to the same procedure for measuring the initial sample (fig. 1(b)).

Test	**Φ_T (%)**	**Φ_f (%)**	**Φ_g**				**Φ_g (%)**	**τ_{c1} (Pa)**	**τ_{c2} (Pa)**
			d<1mm	**d<2mm**	**d<5mm**	**d<10mm**			
1	30	30	-	-	-	-	-	40.74	27.16
2	32	32	-	-	-	-	-	93.32	75.51
3	30	22	8	-	-	-	8	17.89	9.61
4	30	17	8	5	-	-	13	10.56	6.52
5	30	15	8	5	2	-	15	9.51	6.70
6	30	14	8	5	2	1	16	7.20	5.81
7	32	24	8	-	-	-	8	34.42	24.76
8	32	19	8	5	-	-	13	17.57	10.65
9	32	16	8	5	3	-	16	17.44	8.95
10	32	15	8	5	3	1	17	14.94	7.47
11	25	25	-	-	-	-	-	9.50	7.24
12	33	25	8	-	-	-	8	17.88	14.72
13	38	25	8	5	-	-	13	34.12	23.10
14	40	25	8	5	2	-	15	55.11	30.18
15	41	25	8	5	2	1	16	77.88	43.59

Table 1 Soil B. Inclined plane tests.

This paper reports 15 tests referred to soil B (see table 1). The first set of tests were carried out using several mixtures having the total solid volumetric concentration Φ_T = 30%, (tests #1 and #3-6 in Table. 1) and Φ_T = 32%, (tests #2 and #7-10 in Table 1), varying the relative content of fine and coarse grains. Test #1 (i.e. $\Phi_T = \Phi_f$ = 30% and Φ_g = 0%) and test #2 (i.e. $\Phi_T = \Phi_f$ = 32% and Φ_g = 0%) are considered as reference tests. The second set of tests (i.e., tests #11-15 in Table. 1) were performed on mixtures having a constant content of fine particle Φ_f = 25%, and a different concentration of coarse particle Φ_g, in order to experience the effects of the increasing content of coarse particles on the rheology of the mixture. On average, each test lasted about ten seconds, from the initial spreading to the complete stoppage of the mixture. According to the lubrication assumption (i.e., material thickness h_0 much smaller than its longitudinal extent), it may be assumed a uniform flow condition for the flowing mixture, and disregarding inertial effects, momentum balance provides the shear stress distribution within the mixture (*Coussot* 2005). Therefore it is possible to calculate static (τ_{c1}) and dynamic (τ_{c2}) yield stress, corresponding to the initiation of motion and the flow stoppage, respectively (being ρ the soil mixture density, g the acceleration of gravity):

$$\tau_{c1} = \rho g h_0 \sin(i_c) \qquad \tau_{c2} = \rho g h_f \sin(i_c) \tag{2}$$

3 DISCUSSION

The experimental results are consistent with the results obtained by different authors who performed similar laboratory tests (e.g. *Schatzmann et al.,* 2009), and show that the rheological behaviour of these suspensions is typical of non-Newtonian fluids with yield stress. The pyroclastic soils analysed in the present study, usually present a very small clay fraction (sometimes even absent) consequently, the mixtures behave as homogeneous fluids in a very small range of solid volumetric concentration, typically less than 10%. Not only the solid content greatly affects the behaviour of these mixtures in terms of yield stress, but also the relative content of coarser particle. Fig.2 shows the relation between the measured values of the static and the dynamic yield stress, and the ratio between the total solid volumetric concentration Φ_T and solid volumetric concentration of fine particles Φ_f (i.e. $\Phi_T/\Phi_f = 1 + \Phi_g/\Phi_f = 1 + V_{sg}/V_{sf}$), for the first set of test (tests #1-#10 table 1).

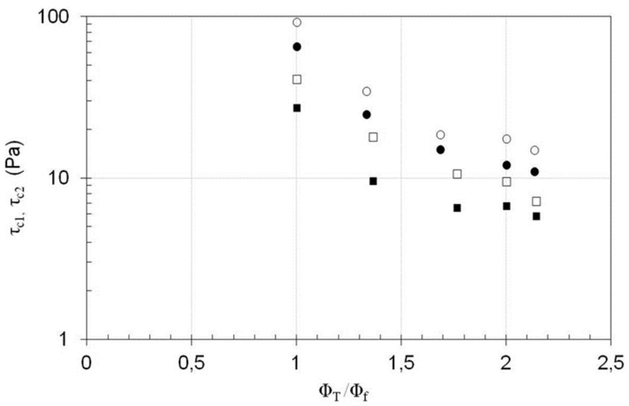

Fig.2. Static (empty symbols) and dynamic (full symbols) yield stress as a function of the ratio between total solid volumetric concentration Φ_T and solid volumetric concentration of fine particles Φ_f (Φ_T = 30% - squares - and Φ_T =32% - circles). (tests #1-10 table 1)

At constant total solid volumetric concentration, 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. It is worth noting that the addition of coarse particles, even though in small quantity, produces a decreasing of the values of the rheological parameters regardless the total solid volumetric concentration of the mixtures (cmp. tests #1-vs-#3 and #2-vs-#7). The presence of just a moderate relative amount of coarse grain (less than 30%), meaningfully reduces both static and dynamic yield stresses (more than 60%) comparing with fine-grained mixture (cmp. tests #1 #3, and #2 #7 in table 1). On the opposite, the reduction of the values of the rheological parameters slightly decrease when the concentration of coarse particles in the mixture are comparable with that of fine grains (tests #4, #5,#6, and #8, #9 e #10 in table 1). Fig.3 reports the experimental results related to the second set of tests (i.e. tests #11-15, Table 1). In this case, being constant the fine particles fraction, the increment of coarse grains concentration (from 8% to 16%) leads to a significant increasing of the value of rheological parameters (by almost one order of magnitude). On the opposite, increasing the volumetric fraction of coarse grains leads to a consistent increasing of the values of the rheological parameters.

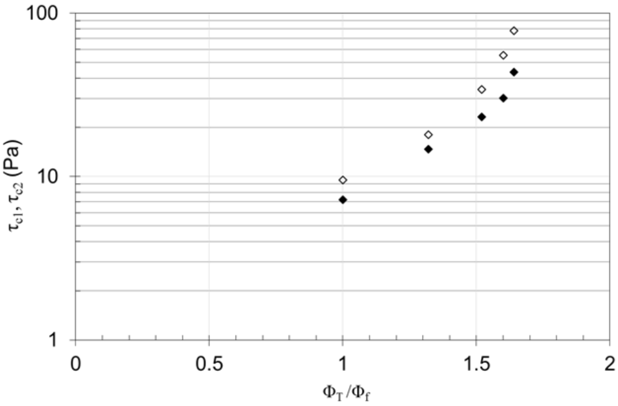

Figure 3 Static (empty symbols) and dynamic (filled symbols) yield stress as a function of the ratio between total solid volumetric concentration Φ_T and solid volumetric concentration of fine particles Φ_f (Φ_f = constant = 25%). (test #5 and tests #17-21, Table 1).

Indeed, in coarse-grained mixtures, the yield stress mainly depends on the inter-particle friction-type contacts, and the increasing of the content of larger particle may leads to an increasing of the yield stress values. It is worth noting that this behaviour corresponds to a threshold value of coarser particle content (about 15%), and it is consistent with the observed results and previous works (e.g., *Coussot & Piau* 1995; *Coussot et al*. 1998; *Ancey and Jorrot* 2001).

4 CONCLUSION

The experiments put in evidence the effect of the grain size distribution on the rheological behaviour of the granular-fluid mixtures, showing that also a moderate content of coarse grain may dramatically affects the rheological behaviour of the material in terms of yield stress.

The relative concentration of coarse and fine particle seems to be discriminant the rheological behaviour: in presence of dominant fine grain fraction, slight increasing of the coarse grain fraction leads to a dramatically 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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